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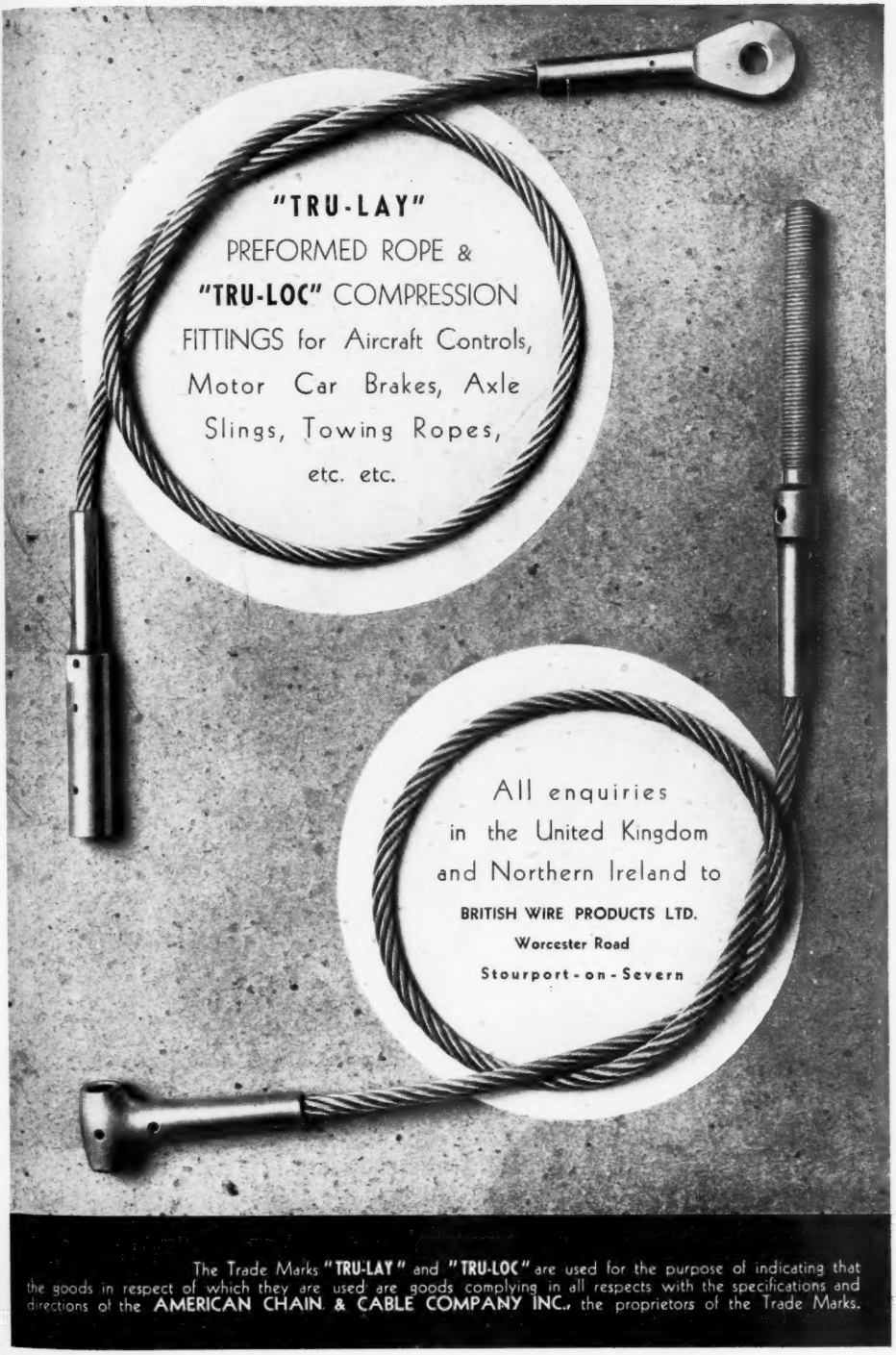

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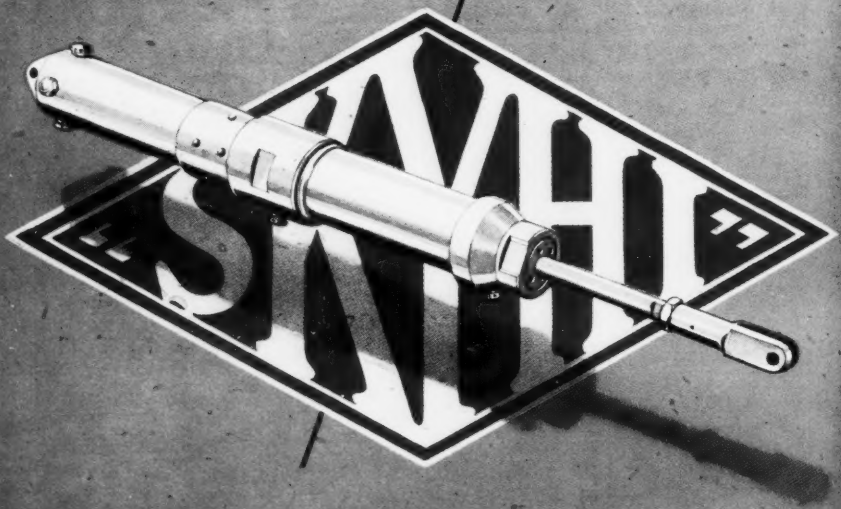

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THE SOCIETY'S PRIZES

The Society offers a number of valuable prizes, most of them annually. Full particulars of the conditions attaching to the awards of these prizes may be obtained on application

Society's Gold Medal

This is the highest honour which the Society can confer for work of an outstanding or fundamental nature in aeronautics.

British Gold Medal for Aeronautics

The British Gold Medal for Aeronautics is awarded for an achievement leading to advancement in aeronautical science.

Simms Gold Medal

The Simms Gold Medal is awarded annually for the best paper read in any year before the Society on any science allied to aeronautics, e.g., meteorology, wireless telegraphy, instruments.

The George Taylor (of Australia) Gold Medal

The Taylor Gold Medal is awarded annually, at the discretion of the Council, for the most valuable paper submitted or read during the previous session.

Wakefield Gold Medal

The Wakefield Gold Medal is awarded annually to the designer of any invention or apparatus tending towards safety in flying, and is open to members or non-members.

Society's Silver Medal

The Society's Silver Medal is awarded, at the discretion of the Council, for some advance in aeronautical design.

British Silver Medal for Aeronautics

The British Silver Medal for Aeronautics is awarded for an achievement leading to advancement in aeronautical science.

Society's Bronze Medal

The Society's Bronze Medal is awarded, at the discretion of the Council, under the same conditions as those for the Silver Medal, but for some less important advance in aeronautical design.

Wilbur Wright Memorial Premium

The Wilbur Wright Memorial Lecture is held annually, a premium of fifty pounds being awarded to the lecturer invited by the Council to deliver the lecture. The lecture is usually given alternately by an American and an Englishman, and is the most important aeronautical lecture of the year. It is delivered whenever possible, on the last Thursday in May of each year.

British Empire Lecture

The Council of the Royal Aeronautical Society have completed the arrangements for the founding of a British Empire Lecture.

The lecture, on any aeronautical subject approved by the Council, will be delivered annually in September in London, by a lecturer, chosen in alternate years from the British Dominions and Colonies and Great Britain.

The Council, by founding this British

Empire Lecture, are anxious to encourage new ideas and new points of view from all parts of the British Empire, and to make the Lecture second only in importance to the Wilbur Wright Memorial Lecture.

The British Empire Lecture will have a premium of £50 attached to it, and in the case of lecturers coming from the Dominions and Colonies an allowance up to £100 will be paid towards the Lecturer's expenses.

It is proposed to hold the first lecture in September, 1945, and suggestions for lecturers should be received by May 31st, 1945, at the latest.

R.38 Memorial Prize

The R.38 Memorial Prize is offered annually for the best paper received by the Society on some subject of a technical nature in the science of aeronautics, preference being given to papers which relate to airships. The prize is twenty-five guineas.

The Herbert Akroyd Stuart Lectures

Under the will of the late Mr. Herbert Akroyd Stuart a sum of £700 is held in trust by the Society for the offer of a prize every two years, for the best paper or lecture read or given before the Society dealing with the Origin and Development of Heavy-oil Aero Engines. The prize is open to members and non-members.

Edward Busk Memorial Prize

The Edward Busk Memorial Prize is offered annually for the best paper received by the Society on some subject of a technical nature in connection with aeroplanes (including seaplanes). Its value is twenty guineas.

Pilcher Memorial Prize

The Pilcher Memorial Prize is offered annually, at the discretion of the Council, for the best paper by a Student on heavier-than-air craft or any analogous subject. Its value is five guineas.

Usborne Prize

The Usborne Prize is offered annually, at the discretion of the Council, for the best paper by a Student on some subject in connection with Aero Engines. Its value is five guineas.

Major Baden-Powell Memorial Prize

The Major Baden-Powell Memorial Prize is awarded in May and December of each year to the student who is considered the best student by the examiners in the Society's Association Fellowship examinations. Its value is three guineas.

Elliott Memorial Prize

The Elliott Memorial Prize is awarded twice yearly to the apprentice at Halton who has the highest percentage of marks in the passing-out examination. Its value is 2½ guineas for each award.

R. P. Alston Memorial Prize

The R. P. Alston Memorial Prize is awarded to any Graduate or Student of the Society for work done leading to improvement in the safety of aircraft, and particularly for improvement in stability and control. Its value is approximately £5.

Branch Prize

The Council offer an annual prize of twenty guineas for the best paper read before the Branches during the previous lecture Session. The prize is open to any member of the Society or of any Branch.

Journal Premium Awards

The Council has set aside an annual sum of £250 to be given as premium awards to authors of papers published in the Journal.

AN APPRECIATION

The Council of the Royal Aeronautical Society wish to thank those Companies who, by their generous co-operation, have done so much to help in the production of the Journal in its new form.

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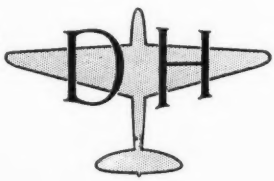

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The Journal of The Royal Aeronautical Society was founded in 1897 in succession to the Annual Reports. For the opinions expressed in Papers that are signed or initialled the authors alone are responsible. None of the papers or paragraphs must be taken as expressing the opinion of the Council of The Royal Aeronautical Society unless such is definitely stated to be the case. **The Journal is published monthly at the Offices of the Society, 4, Hamilton Place, Piccadilly, London, W.1.** Subscriptions per annum, £4 10 0 post free; Single Numbers 7/6 or 7/9 post free. All communications for publication in the Journal, or on general matters affecting the Society should be addressed to—The Secretary, J. Laurence Pritchard, 4, Hamilton Place, W.1. The Society's Bankers are Messrs. Coutts and Co. All communications respecting Advertisement matters should be addressed to—The Advertisement Manager, Journal of The Royal Aeronautical Society, 4, Hamilton Place, W.1.

Telephone: Grosvenor 3515-3516-3517. Telegraphic Address: Didaskolas, Audley, London.

SEPTEMBER NOTICES 1945

JOURNAL PREMIUM AWARDS

The Council have set aside an annual sum of £250 for the award of premiums for papers published in the *Journal* and the Council hope that members will contribute papers on their own special subjects.

Contents of the September Journal

Electrics for Aircraft, by C. G. A. Woodford, A.F.R.Ae.S.

Modern Experimental Work on Aeroplane Structures, by Dr. A. G. Pugsley, F.R.Ae.S.

Wing Testing, by H. H. Gardner, B.Sc.

Lecture Programme

The following Lectures have been arranged for the first half of the 1945-1946 Lecture Session. Members are admitted without tickets, but non-members must obtain tickets through a member.

The Lectures will be held at 6.30 p.m. in the Lecture Theatre of the Institution of Mechanical Engineers, Storey's Gate, St. James's, S.W.1 (by permission of the Council of the Institution).

October 4th—The Future Scope of Propellers, by Mr. L. G. Fairhurst.

October 18th—Aircraft Engine Oil Cooling, by Mr. F. Nixon, B.Sc., M.I.Aut.E., F.R.Ae.S.

November 1st—A Critical Review of German Long-range Rocket Development, Mr. W. G. A. Perring, F.R.Ae.S.

November 15th (First British Empire Lecture)—Australian and Empire Air Transport, by Mr. W. Hudson Fysh, D.F.C.

November 29th—Aspects of German Aeronautical Development, by W. J. Stern.

December 11th—Meteorology and High Altitude Aviation, by Professor Dobson, F.R.S.

The following lecture will be delivered in the Institute of Civil Engineers, Great George Street, S.W.1, at 6.30 p.m.

December 19th—Atomic Disintegration, by Professor N. Feather, F.R.S.

Branch Lectures

COVENTRY BRANCH

September 20th—Gas Turbines for Aircraft Propulsion, by Dr. S. G. Hooker.

October 18th—Hydraulics, by S. M. Parker, B.Sc., A.F.R.Ae.S.

November 22nd—Modern Experimental Work in Aircraft Structures, by Professor A. G. Pugsley, F.R.Ae.S.

Lectures will be held in the Council Staff Canteen, Old Gulson Library, at 7 p.m.

DERBY BRANCH

Lectures by the following have been arranged and will be held in the Rolls-Royce Welfare Hall, Nightingale Road, Derby:—

October 1st—Dr. F. W. Hilton, of the National Physical Laboratory.

November 5th—Air Commodore Vernon Brown, C.B., O.B.E., M.A., F.R.Ae.S., and Wing Commander N. G. Bennett, M.B.E. (Air Ministry Accidents Investigation Branch).

December 3rd—Annual General Meeting.

GLASGOW BRANCH

September 20th—Films and Discussion.

October 17th—Light Alloys for Aircraft, by Mr. F. Kasz, A.R.Ae.S.

November 15th—Fuel Injection, by Mr. Morris.

Meetings will be held in the Royal Technical College, George Street, Glasgow, at 7.30 p.m.

Associate Fellowship Examinations—December, 1945

Intending candidates for the Associate Fellowship Examinations in December, 1945, are reminded that the closing date for entry is September 30th, 1945. Entry forms may be obtained from the Secretary.

New Zealand Branch

The Council at their meeting on August 23rd, 1945, approved the formation of a Branch of the Society in New Zealand. Will those interested write to:—

Mr. T. T. N. Coleridge, B.E., A.F.R.Ae.S., c/o The Shell Co. of N.Z., Limited, P.O. Box 1663, Wellington, N.Z.

Reading Branch

The Council at their meeting on August 23rd, 1945, approved the formation of a Branch of the Society in Reading. Will those interested write to:—

Mr. B. Buck, A.F.R.Ae.S., Miles Aircraft, Limited, The Aerodrome, Reading, Berks.

Election of Members

The following members were recently elected:—

Associate Fellows

John Edward Chorlton (from Companion), John Edward Greenhalgh, William Redvers Kilminster (from Associate), Ronald Little, Leo A. McQuillin (from Graduate), David Wadsworth, Arthur Winks, William Wittels.

Companion

Sitarama Viswantha Iyer.

Associates

O. T. S. Balasubramanian, John Parr (from Student), Cecil Thomas Prior, Ernest William Reed, Jan Constantine Stark, Geoffrey Verdon - Roe (from Student), Frederick Henry Young.

Graduates

Richard Anthony Phillips Anderton, Douglas Frank Denny (from Student), Joseph Glynn Ouseley (from Student), Frederick Robert Robinson.

Students

Christopher Richard Baines.

Additions to the Library

Pamphlets in italics with location reference following in brackets. Books marked * may not be taken out on loan.

A.c.17.—Thermodynamic Properties of Air. J. H. Keenan and J. Kaye. John Wiley & Sons. 1945. $4.25.

B.a.340.—*Heinkel He.177 A-5. (Press release 26/7/45.) Ministry of Aircraft Production.* (Y.3.iii.37.)

*B.a.341.—The Fairey " Firefly IIM " Aircraft. Fairey Aviation Co.

*B.a.342.—The Fairey IIIF Aircraft. Fairey Aviation Co. 1932.

B.a.343.—Fokker. Nederlandsche Vliegtuigenfabrik 1919-1929. 1929.

B.f.89.—Abhandlungen aus dem Gebiete der Naturwissenschaften Band xiv: Zur Mechanik des Vogelfluges. F. Ahlborn. Friederichsen & Co. 1896. (Folio.)

BB.b.114.—Mechanics of Aircraft Structures. John E. Younger. McGraw-Hill Publishing Co. 1942. 20/-.

*E.b.108.—Experimental Stress Analysis. Vol. 2, No. 2. Society for Experimental Stress Analysis. Addison-Wesley Press, Inc. 1945.

E.e.14.—The Health and Efficiency of Munition Workers. H. M. Vernon. Oxford Medical Publications. 1940. 8/6.

NOTICES

*J.g.212.—*Smithsonian Miscellaneous Collections, Vol.* 104, *No.* 12. *Roebling Fund. The Solar Constant and Sunspot Numbers.* (Y.30.i.)

K.c.21.—*Long-range German Rocket V2. (Press release,* 26/7/45.) *Ministry of Aircraft Production.* (Y.3.iii.38.)

L.a.50.—Fly with Me. Victor Ricketts. Hurst & Blackett. 1939. 1/-.

L.b.44.—Aviation. H. E. Wimperis. Oxford University Press. 1945. 3/6.

R.b.255.—Das Flugprincip: eine populärwissenschaftliche Naturstudie als Grundlage zur Lösung des Flugproblems. Carl Buttenstedt. Carl Blankenberg's Druckerei und Verlag. 1893.

R.b.256.—Die Luftschiffarht und die lenkbaren Ballons. Henri de Graffigny. Carl Reissner. 1888.

R.b.257.—*Switzerland from a Balloon. Charles Herbert. (Strand Magazine,* 1899.) *PR* 1/3*c*.

R.c.281.—La Conquête de l'Air. L. Sazerac de Forge. Berger-Levraut & Cie. 1907.

S.a.144.—Death in the Air: the diary of a Flying Corps Pilot. William Heinemann. 1933. 6/-.

S.a.145.—The Air V.C.s. Capt. W. E. Johns. John Hamilton. 5/6.

S.e.86.—"So Few": the Immortal Record of the R.A.F. D. Masters. Eyre & Spottiswoode. 1941. 3/-.

S.e.87.—Wings in Exile: Life and Work of the Czecho-Slovak Airmen in France and Great Britain. Ed. Bohus Benes. Czechoslovak Independent Weekly. 1942. 5/6.

S.e.88.—Squadron 303. The Polish Fighter Squadron with the R.A.F. Arkady Fiedler. Peter Davies. 1942. 6/6.

T.a.113.—Waves, Wheels, Wings: an Autobiography. Sir Walter Windham. Hutchinson & Co. 1940. 7/6.

T.a.114.—Soldier and Aviator: Capt. Patrick Hamilton, R.F.C. Ethel Hamilton. C. W. Daniel. 1912. 5/-.

T.b.91.—Twenty Thousand Miles in a Flying Boat. Sir Alan Cobham. George Harrap & Co. 1930. 6/6.

T.b.92.—Skyward. Richard Evelyn Byrd. G. P. Putnam & Sons. 1928. 12/6.

T.b.93.—The Great Trans-Pacific Flight. C. E. Kingsford Smith & C. T. P. Ulm. Hutchinson & Co. 1928. 10/6.

T.b.94.—Flying Gipsies. Violette de Sibour. G. P. Putnam & Sons. 1930. 7/6.

TT.a.49.—The High Courts of Heaven. J. W. Hewes. Peter Davies. 1942. 6/6.

TT.a.50.—Readiness at Dawn. "Blake" Victor Gollancz. 1941. 5/6.

J. Laurence Pritchard,
Secretary.

ELECTRICS FOR AIRCRAFT

by

C. G. A. Woodford, A.M.I.E.E., A.F.R.Ae.S.

C. G. A. Woodford joined the Admiralty in 1923, working on electrical equipment and engines. In 1938 he joined the Air Ministry and was appointed Assistant Director (Signals) in 1941. He was a member of Sir Roy Fedden's mission to America in 1943. He is now with the English Electric Co. He has been an Associate Fellow of the Society since 1943.

A MEETING of the Royal Aeronautical Society was held in the lecture hall of the Institution of Mechanical Engineers at Storey's Gate, St. James's Park, Westminster, London, S.W.1, on Thursday, March 8th, 1945, at which a paper on "Electrics for Aircraft," by Mr. C. G. A. Woodford, A.M.I.E.E., A.F.R.Ae.S., was read and discussed. The President, Sir Roy Fedden, in the Chair.

THE CHAIRMAN, introducing Mr. Woodford, said that although the problem of electrics for aircraft was ancillary, it was continually becoming more prominent. As a power plant man, he felt certain they were in for a big development in electrics; and as he did not see much more in the D/C line than 6 kW., he was greatly in favour of the view that A/C supply at about 200 volts, 400 c/s., should be the scheme for the future.

Mr. Woodford had joined the Air Ministry in 1938, having served previously with the Admiralty. When Sir Stafford Cripps had sent the Chairman, with 11 other engineers, to America for a few months at the beginning of 1943, in order to study production methods, Mr. Woodford was one of the mission. They had travelled more than 14,000 miles and had visited between 40 and 50 plants. In a trip of that sort the members of the party got to know each other very well, and he had formed a very high opinion of Mr. Woodford's work and of his keenness and enthusiasm for his subject.

1. *Introduction*

RECENT discussions indicate that the time is ripe for British aviation to benefit from a wider use of electrical ancillary equipment. There has, in the past, been a lack of appreciation, on the one hand, of what such benefits could be, and on the other, of the special needs of aircraft in regard to the right type of electrical equipment. There is thus a gap to be bridged in getting the aeronautical engineer and aircraft designer, who are essentially specialist mechanical engineers, to become more electrically minded, and also in providing them with lightweight, compact and utterly reliable apparatus so that aircraft may in the future be fitted with generators,

motors and other accessories of the " fit and forget " quality, embodying the requisite degree of suitability for purpose.

It might be supposed that the right sort of equipment could easily be developed and then made available to the user, but there is always a tendency for the supply of rather special equipment to lag behind the need, through lack of inspiration and intelligent anticipation. Much of the development of aircraft services has hitherto been the outcome of modifications to the original basic design, and designers can obviously only incorporate methods of operation or control which have been proven by practical trials. It is, therefore, important at the present time that the designers of new aircraft of whatever size and type should have before them a clear picture of what will be available to them of electrical equipment. It is equally necessary that the manufacturers of this equipment should have a reliable guide as to the probable needs in range of equipment and quantities.

It is hoped that these notes will assist in crystallising the views of the aircraft designer as to what he might advantageously use and so help to indicate what should be made available for the next and following phases of aircraft development. These considerations will also have some bearing on power unit design since the incorporation of larger capacity generators and more engine accessory equipment will affect the layout of rear sections of engines and nacelles.

2. *Application of Electrical Services*

Object of Electrifying Services

There is a manifest desire to reduce the number and diversity of types of ancillary power services, and a recognition that the higher transmission efficiency with electrics gives some saving in weight of fuel to be carried.

Moreover, the increase in higher load factor services, such as radio, heating, lighting, armament and flying services, will not only improve the general efficiency, but in addition bring generators into use with larger capacity so that the higher power but infrequent services such as landing gear and flaps can be operated in much shorter times than in the past.

Directions in which new applications are expected to arise may be briefly summarised as:—

(i) Operational or users' requirements, including armament, communication, navigation and reconnaissance.

(ii) Designers' improvements to save manual effort and replace complex mechanical controls of secondary and minor operations.

(iii) Introduction to provide servo or power operations of important flying services and other services required in the air or on the ground.

(iv) Introduction of automatic devices for improved performance or comfort.

(v) Control of non-electric power services to save space, weight and vulnerability and to simplify installations.

(vi) Replacement of non-electric power services to reduce diversity of types, improve load factor and simplify production and servicing.

(vii) Introduction of heating for personnel and cabins and special equipment and also cooking, etc.

It is not the purpose of this paper to deal with electrical equipment of highly specialised operational kinds, such as for navigational, armament, communication or flight instruments, beyond noting the increasing demand upon the electrical system thereby entailed, and the effect of this on the development of electrical ancillary operations. A great deal of such equipment requires alternating current power supply at 400 c/s, and future radio apparatus will need a higher frequency which can be readily obtained by converting from the main system. For the saving of power and weight it is desirable that individual converter or inverter sets should be as few as possible, and there will be a

preference for an electrical system designed essentially for the widest range of sizes and types of aircraft, and able to meet the widest variety of conditions in the operation of services and equipment.

3. *Power Supply*

(*a*) *Present Limitations*

Lack of electric power supply has been associated with the general backwardness of electrical developments in aircraft, and is itself in part due to limitations peculiar to aircraft conditions. Space on the accessory section of a high performance aircraft engine is very limited and it has usually been required to mount a whole family of individual accessories. The overall and mounting flange dimensions of these, in particular of generators, and the meagre permissible torques, overhung mass and moment of inertia, have tended to restrict the scope of ancillary power service development.

It would seem that the established practice of using an auxiliary services gearbox on each engine with a limited number of outlets should be seriously reviewed in favour of a generator of substantial capacity being substituted from which any number of services can be supplied electrically. Advantage could then be taken of running the generator at the highest practicable speed for reduction of weight and space, and greatly simplifying the ancillary systems, with good facilities for adding services required by operational developments.

In aircraft generators, limiting factors are met in the commutators, brushgear and commutating poles essential with direct current. By restricting speed, taking up volume for non-generating parts, making sources of losses, and generally adding to the difficulty of cooling, commutation militates against the reduction of space and weight. These difficulties have been increased by high altitude conditions, which have given rise to special problems of excessive brush wear. Various aspects of brush lubrication have been investigated and new compositions developed with much improved endurance; but, with the undoubted tendency for conditions of radiation in the substratosphere to enhance ionisation, it is tolerably certain that from all considerations commutator brushgear would remain a serious limiting factor in aircraft generators and motors as regards weight, size, performance, maintenance and reliability.

The larger aircraft and the increases in electrical loads require a higher pressure for savings in cable weight and elimination of volt drops problems. It is, however, important to avoid a multiplicity of systems, and if a change is called for, it should be to one suitable for a wide range of aircraft. The large military aircraft, now equipped with direct current installations, therefore may well be regarded as the limiting size for low pressure d.c., and a change over to medium pressure alternating current is expected in the near future. This view is considerably strengthened by the possibility of carrying an auxiliary generating plant capable for comparable weight of a sustained emergency or standby supply which a battery could give for a short time only. This being so, we are no longer tied to d.c.

(*b*) *Possibilities of Alternating Current*

It is most desirable that the ancillary power system should be suitable for the widest variety and size of aircraft, and to remain suitable for any probable development in the operational conditions, such as long endurance, high altitude and extremes of climate.

An alternating current system is particularly favourable through the virtual elimination of commutators and brush gear, and the adoption of simple types of generators and motors. Such machines, by the use of glass insulation and bakelised treatment with stationary main windings, and of practically solid rotors, represent an entirely new conception of aircraft electrical machines, able to run at high speeds with high overload capacity and safe temperature ranges.

and in which servicing is reduced to that for ball bearings.

Freedom from radio interference due to sparking commutators is another great advantage with the elimination of suppressors, and contact breaking equipment can in general be lighter and more compact than for direct current. A further benefit can be expected from reduced risk of service failure due to circuit damage, which, while being of quite infrequent occurrence generally, would have a greater probability of interruption on d.c. with either single or double pole wiring, compared with a.c., in which, if necessary, the neutral point may everywhere be connected to airframe so as to allow 2-phase working in case of a broken line.

Suggestions have been made in the last year or two that electric ancillary power should be generated in the form of alternating current and converted by static rectifiers into low pressure direct current to supply the enlarged systems which have grown up during the war, and at first sight there are a number of attractive features for such an arrangement, *e.g.*, the ability to operate the generators over a wide range of speed and frequency while maintaining through suitable regulators a sufficiently uniform d.c. pressure with or without the usual accumulator. Such an arrangement might well offer a possible interim solution to the problem of providing more adequate generator capacity, while at the same time permitting the continued use of available equipment.

It will, however, be felt that such a scheme could only be regarded as a wartime palliative measure and not to be recommended for future adoption to meet the requirements and operational conditions indicated above.

(*c*) *Consideration of Voltage*

In determining the most suitable a.c. pressure to be adopted, it is visualised that aircraft sizes down to 50,000 lbs. A.U.W. would certainly be covered. Smaller types could also be standardised on the adopted system without difficulty. Below 25,000 lbs. it would be preferable not to have to carry standby generating plant, and as this feature is bound up with ground electric services, local arrangements should be such that the aircraft supply will be available from converters or portable generators at all necessary locations for aircraft on regular operations.

The object, therefore, is to standardise an a.c. system at a medium pressure which will (*a*) be suitable for all sizes of military and civil transport aircraft, (*b*) be suitable for reliable operation and endurance at all flying altitudes, (*c*) be safe for passengers and operating crew, (*d*) give maximum economy in production, installation and operation.

General considerations, including the avoidance of adding more than one new system to the existing low pressure direct current, indicate that any change should be to three-phase a.c. at medium pressure. At present, one British military type, the Shetland, has been engineered with 110-volt equipment and two American military types are being designed which will have 200-volt equipment on a 208-volt 3-phase system in which each phase line is at a potential of 120 volts to the airframe.

In the Shetland the system is wholly insulated from the airframe, while in the American types the neutral point will be connected to airframe and thus limit the shock voltage for personnel to about 120 r.m.s. (or 120×1.414 peak volts).

In civil transport types there is no appreciable risk of shock to passengers and the danger to crew would not be serious for any medium pressure below 250 volts with the neutral of the system connected to airframe.

In regard to risk of fire, the possibility of sparks from damaged cables, etc., would increase with higher pressures, but the risk would not be appreciably greater with 200 to 250 volts than with 110 volts.

There is saving in weight on cables in the larger aircraft with pressures up to about 250 volts. At appreciably higher pressures

the saving on copper would be limited by strength requirements in small cables and there would be an increase in size and weight for insulation, and reductions in space factor and heat conducting in machine windings.

These considerations indicate not less than 200 volts to be the most suitable pressure, with the neutral grounded to the airframe. This will almost certainly be widely adopted for civil transport aircraft and has lately been approved for military types of the future.

(d) Consideration of Frequency

Within limits, the higher the frequency the greater the saving on weight of iron cores of motors, alternators and transformers. It has been recognised in this country and in America that the best choice for weight saving is in the region of 300 cycles per second.

In the past few years there have been isolated experimental installations employing frequencies of from 233 c/s to 800 c/s, the lowest value quoted being for rectification to d.c. In 1939 there was a widely held preference in England, France and America in favour of 400 c/s. The system designed for the Shetland was a 250 c/s, and systems being designed for new U.S. military types are on 400 c/s.

Supplies through inverters for a.c. instruments, automatic pilots and fire control are at 400 c/s, whether single-phase or three-phase, with a possible few exceptions.

In regard to supplies for radio, present communication and beam approach equipment have d.c. fed power units and could employ somewhat similar converters to operate from any other supply at whatever frequency is adopted, or static rectifier units could be provided. Special radio flying aids at present operate on 1200-2400 c/s generators, and although efficient power packs could be designed for 800 c/s or 400 c/s, a higher frequency, say, 1600 c/s, would be preferred in most cases. At the same time a few smaller requirements could be operated direct off 400 c/s. The general position on radio is therefore that the greater part of the supply would be converted to a preferred higher frequency. It would, however, be better to convert from 400 c/s than from 250 c/s.

As regards alternator speeds, only frequencies of 250 and 400 c/s need be considered. For 250 c/s speeds can be 15,000 r.p.m., 7,500 r.p.m., 5,000 r.p.m. or 3,750 r.p.m. for 2, 4, 6 or 8 poles. At 400 c/s the speeds are 24,000 r.p.m., 12,000 r.p.m., 8,000 r.p.m., 6,000 r.p.m. or 4,000 r.p.m. for 2, 4, 6, 8 or 12 poles.

For direct drives by auxiliary engines, 4,000 r.p.m. should not be exceeded; for geared drives off main engines, generator speeds up to 12,000 r.p.m. are suitable, and for turbo alternators speeds up to 24,000 r.p.m. should be aimed at for the smallest weight and size. Hence on this point there seems little at present to choose between 250 and 400 c/s, but with the possibility of turbo developments in mind and the wider choice of speeds available, a preference for 400 c/s is justified.

For motor speeds, the choice of nominal speeds available for simple induction motors is 15,000 or 7,500 r.p.m. for 250 c/s (2 pole and 4 pole) and 12,000 or 8,000 r.p.m. for 400 c/s (4 pole or 6 pole). Thus 400 c/s offers a better choice of speeds, *i.e.*, 8,000 r.p.m. for the larger motors as more suitable for gearing, and 12,000 r.p.m. for small motors, and avoiding the use of 2-pole motor construction which is less favourable in several points of design.

As between 4-pole motors on 250 c/s and 6-pole motors on 400 c/s there is a reduction in power factor and efficiency of a few per cent. on 400 c/s, which is not regarded as serious or sufficient to upset the general balance in favour of 400 c/s. It should be noted that higher torque motors will operate at somewhat lower speeds than the nominal values given above.

In the interests of standardisation between Britain and America both in instruments and

other electrical equipment, it is expedient therefore to adopt 400 c/s as the standard as this frequency will have no appreciable disadvantages in the weight and efficiency of equipment, and offers a more suitable range of speeds for motors and alternators than does 250 c/s. 400 c/s will also be more favourable for the operation of turbo alternators at high speed. The higher frequency is preferred for power supply to radio, both as regards design of equipment for direct supply and for conversion to higher frequency for special purposes.

(e) Main Engine-driven Generators

Generators driven by the simplest method from the main engines offer the most efficient source of ancillary power, by virtue of the high state of development of the aero engine as regards reliability and efficiency. The power delivered to the generator is unaffected by altitude. It will therefore generally be preferred that all power required in flight should normally be obtained from the most compact form of generator of adequate capacity fitted on each power plant unit up to a maximum of four, as will be made more clear when the distribution of power is considered later. The highest practicable speed should be adopted to reduce weight and size with accompanying benefit in short internal connections and consequent saving of losses.

Main particulars of typical generators are given in the tables overleaf.

Present indications are that the rated speeds may be limited to 8,000 r.p.m. instead of 10,000 r.p.m. for American types, and the British types are being designed for an engine speed range of 0.75 to 1.33 times maximum continuous cruising speed of about 2,300 r.p.m., with 6,000 r.p.m. for dive and 7,200 for overspeed test.

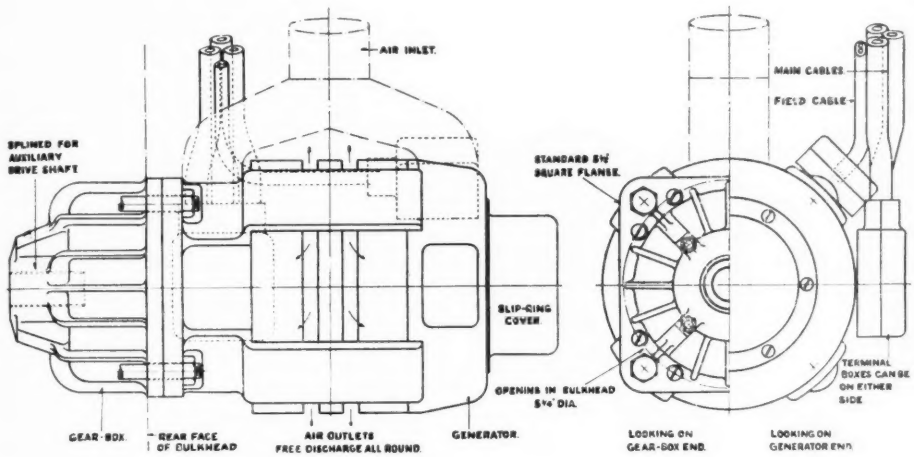


Fig. 1
Outline of 12/16 kw. A.C. Generator and Gear Box.

Reviewing the relative weights of engine-driven generators, it is significant to note that the small capacity d.c. machines in use at the beginning of the war gave about 25 watts per lb., while the present type of alternator for 8,000 r.p.m. gives about ten times this specific output, and further improved power/weights performances is expected with higher speed.

Fig. 1 shows an outline of a typical engine-driven alternator arranged with a standard square mounting flange and having a speed

TABLE 1

British d.c. Generators

Type Ref.	Output.		Speed (r.p.m.)	Weight (lbs.)	Size (ins.)	
	Volts.	Amps.			Length.	O/diam.
K	29	40	3500/6000	34	11+2	$5\frac{1}{2}$
KX	29	60	3400/6000	34		
O	29	120	3300/6000	57	12+2	6
P	30	200	3300/4800	56	$12\frac{1}{4}+1\frac{1}{2}$	7
O2	29	120	3300/6000	34	11+2	$5\frac{1}{2}$

TABLE 2

American d.c. Generators

Type Ref.	Output.		Speed (r.p.m.)	Weight (lbs.)	Size (ins.)	
	Volts.	Amps.			Length.	O/diam.
O.1	29	100	2500/4500	33*	$11\frac{3}{4}$	6
O.2	29	100	4400/10000	26	$10\frac{3}{4}$	
P.1	29	200	2500/4500	45*	14	6
P.2	29	200	4400/10000	34	$11\frac{1}{2}$	6
R.1	29	300	4400/8000	47*	14	$6\frac{3}{8}$

* Includes airspout at non-drive end.

TABLE 3

British a.c. Generators (3-phase)

Type Ref.	Output (kw.)*	Rating (at 0.8 p.f.)		Frequency (c/s).	Speed (r.p.m.)	Weight (lbs.)†	Size (ins.)	
		Volts.	Amps.*				Length.	O/diam.
Y	5	115	30	250	7500			
	24	208	105	400	8000	64		
	12	208	52	400	8000	44	10	7
	6	208	26	400	8000	25		
	3	208	13	400	8000	16		

* Maximum overload is one-third greater. † Estimated (without exciter).

TABLE 4

American a.c. Generators (3-phase)

Type Ref.	Output (kw.)	Rating (at 0.75 p.f.)		Frequency (c/s.)	Speed (r.p.m.)	Weight (lbs.)	Size (ins.)	
		Volts.	Amps.				Length.	O/diam.
(G.E.)	40	208	145	400	6000	83.5	17	$9\frac{1}{4}$
Westing-house	24	120	150	400	8000	53.6		
,,	30	208	100	400	6000	85*	19	$9\frac{1}{2}$
,,	42	208	111	400	6000	85		
Eclipse	18.75	208	70	400	8000	49*		5
,,	50	208	185	400	6000	129*		10

* Including exciter.

increasing gearbox mounted in common with it. This gearbox has an overload slipping device which will enable a momentary short circuit peak load to be safely accepted without the need for a special weak point in the drive, in order that continuity of supply can be ensured with the clearing of any likely fault occurrence due to combat or other damage.

vices in an emergency or on the ground, developments in operational conditions have shown the limitations of accumulators, and the growth in size and number of the services to be kept going under various conditions has turned attention to the possibilities of small auxiliary generating plants with petrol engines. Such a set can give a steady output at sea level or low altitude, for any periods

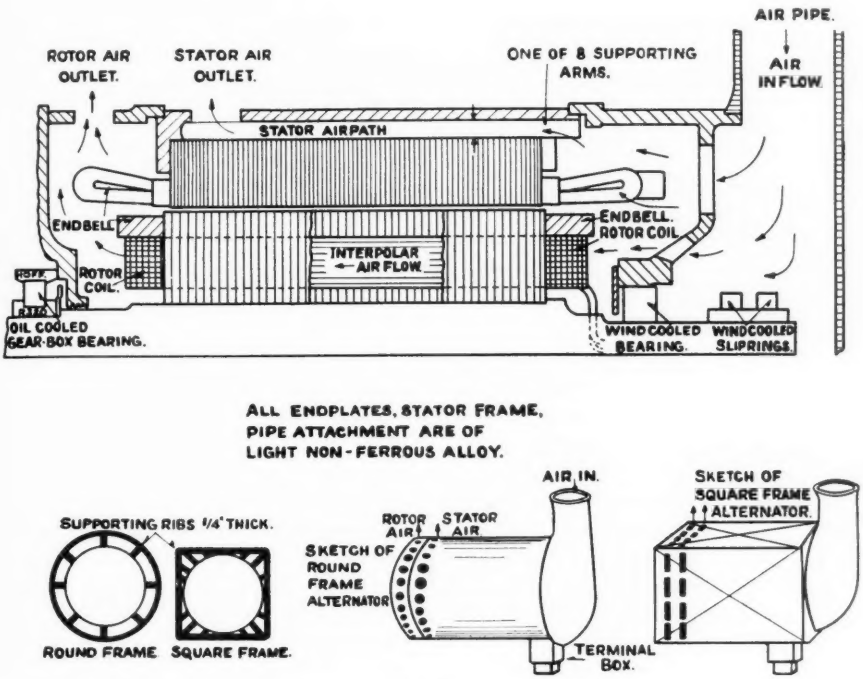


Fig. 2
Layout of Alternator for Axial Cooling Blast.

This diagram is reproduced through the courtesy of Mr. S. Neville, at M.A.P.

Fig. 2 shows the appearance of a typical alternator arranged for axial ventilation by air blast.

(f) Auxiliary Generating Plant

Whereas in the past it has been generally thought that an aircraft must depend on a storage battery to supply the essential ser-

likely to be necessary, for about the same weight as a battery which would run down in, say, a quarter of an hour.

Such auxiliary sets should, wherever possible, be fitted with the same type of generator as those on the main power plant to ensure retraction of undercarriage in the event of an engine cutting out during take-off; they would be used on the ground when distant from the normal aircraft ground

supply, for standby against main engine failure at take-off or in the air, and when coming in to land, particularly in passenger aircraft requiring adequate steady lighting and other passenger amenities. The auxiliary generating plant would almost certainly be arranged as a detachable unit for quick servicing and would generally be replaceable by extra cargo when called for on short journeys.

In twin-engine aircraft use might be made of the a.g.p., even at reduced output at operational altitude, for supplementing the main generators on cooking loads or other occasional services, thereby avoiding the necessity for rather larger generators in such aircraft.

In the case of flying boats where augmented power supply would be frequently required while on the water, two auxiliary sets would generally be necessary in addition to the complement of main engine generators.

Freedom from the need for an aircraft accumulator through the general use of an auxiliary generator removes the only technical obstacle to the adoption of an alternating current system, and in such a system the a.g.p. could form the standby for a constant voltage and frequency supply for instruments, etc., as well as for the general supply from the main engine drive generators.

For the immediate future, however, the utility of a suitable a.g.p. with direct current generator is evident. The increase of electrical power requirements is likely to continue even in existing types of aircraft, but it will hardly be thought feasible to change over important military types to alternating current systems during present war conditions, in spite of the considerable benefits which such a change might offer. Accordingly, with the limitation in capacity of d.c. generators and accumulators, an a.g.p. for additional d.c. supply during general flight and combat conditions appears necessary, but it is to be hoped that the development and introduction of such a set will not obscure the argument already deduced in favour of the more simple and efficient scheme based on main engine alternators for general supply, with the a.g.p. for standby, and without the special arrangements for sustained running at the higher operational altitudes.

Nevertheless, any experience which can be gained, before the end of hostilities, of running a.g.p. in British aircraft will be of great value. The opportunity of such experience should be wisely used by choosing present running conditions to simulate future conditions necessary for the a.c. system, particularly in regard to the engine and generator driving arrangements. Observing that 8,000 r.p.m. is the present nominal speed for main engine-driven alternators and that the latest American d.c. generator Type R is also suitable for this speed, it is clearly desirable that auxiliary engines for such sets should be arranged with generator drives for 8,000 r.p.m., and possibly 12,000 r.p.m. as alternatives. The engine would, presumably, be suitable for running at not less than 3,000 r.p.m. over long periods in flight for immediate needs, say, with d.c. generators, and for about the same weight should be suitable for greater output at, say, 4,000 r.p.m., with an alternator for standby use, on the future a.c. system.

Weight will be an important consideration in regard to standby supply arrangements. The conception of the a.g.p. installation must not be over-elaborate with a penalty in weight. In large aircraft it could be located in proximity to main power plant in order to simplify installation requirements while preserving accessibility. In smaller aircraft, where an inboard location might be necessary, the relatively small amount of running during flight should permit of a simple and light installation. It is in the smaller aircraft that the choice between a battery and an a.g.p. is probably less clear, but since it is found necessary to allow about 150 lbs. for a battery in a 40,000 lb. passenger aircraft in a d.c. system, there

seems to be a good chance of effecting an overall saving in weight and efficiency with an a.g.p. of similar weight to the battery, working in an a.c. system.

(g) Gas-driven Turbo Alternators

The possibility of driving high-speed alternators from exhaust gas turbines is very attractive, particularly in view of the good use which has already been made of superchargers driven in this way, with a margin of surplus power available at the waste gate.

On the frequency of 400 c/s a speed of 24,000 r.p.m. would be suitable for lightest weight, in the case of the simple 2-pole rotor.

It seems highly probable that generation of ancillary power in this way would be more efficient in fuel and installation weight than with engine-driven generators, and the ancillary system might conceivably be resolved into two turbo alternator units, each of normal capacity for at least two-thirds of the regular demand with provision for transferring services from either to the other if shut down. The layout should be such that each turbine could receive exhaust gas from either of two separate power plants in a multi-engine aircraft, and consideration should then be given to the provision of a standby fuel burner for use on the ground or in emergency.

In regard to the latter, such a scheme might form part of a cabin heating system for flying boats when on the water.

(h) Voltage and Frequency Regulation

With the increase in precision instruments, radio and equipment depending for correct functioning on a well-regulated power supply, problems arise from the variations in speed and load, due to the characteristics of both generators and batteries. Further complication is added where parallel operation of generators is concerned.

Up to the present, all forms of voltage regulation have been based on the conditions necessary for maintaining a charged battery in the system which can only discharge through a reduction of pressure to, say, 22 volts or less, from the level of about 28 volts when the full service is borne by the generators. This condition has given rise to the need for a number of independent voltage regulators and special power units for individual equipment items, and has lately led to consideration of means for master voltage regulation of the whole system with several machines in parallel, combined with a finer control of the individual generators for load sharing.

The elimination of batteries for standby would simplify this problem.

In alternating current installations the questions of voltage and frequency regulation arise in different form. The chief difference between main engine and auxiliary driven alternators from the electrical standpoint is that the former will vary in speed and frequency, although not because of electrical load, whereas the latter can be run at fairly constant speed apart from the momentary effects of sudden load.

This aspect leads to two considerations, viz., whether parallel operation is of any consequence and whether constant speed drives are necessary. Experience shows that paralleling of aircraft generators is no substitute for the provision of adequate capacity and it is preferable to subdivide the connected loads so that they can be supplied by the most direct route with provision for automatic changeover for essential services in military types, and possibly manual changeover in large civil types. The disturbing effect of sudden overloads or faults is thereby avoided, and equipment is kept simple.

For the main engine-driven generators the simplest possible arrangement would be a direct drive with speed and frequency varying in step with engine speed. Such an arrangement would be quite suitable for all motor-driven services, and would in fact be equivalent to mechanical drives from the engine, with the electrical link between

generator and motor behaving like a shaft of unlimited flexibility, since the motor would run in step with engine speed.

It will be clear that to control the frequency of an a.c. system to a more or less constant value would necessitate the provision of some form of constant speed drive. Consideration has been given to slipping clutches, variable gearboxes, eddy current couplings and hydraulic couplings, but these have common drawbacks in the weight and space taken up and the introduction of a source of inefficiency and unreliability. A constant speed drive probably of hydraulic torque converting type will no doubt be developed if there is shown to be need of such, and interesting types are in advanced stages both here and in America, but the indications are that excessive weight is involved in meeting wide range in engine speed.

It is, moreover, doubtful whether a simple enough means of speed control would be forthcoming to warrant its being fitted on every generator drive, especially as it is doubtful whether paralleling of generators can be considered worth while. The preferred alternative course seems therefore to adopt the simplicity of variable frequency operation for motor-driven services with a converter for the constant frequency services, the a.g.p. acting additionally as standby for these services, as already indicated.

The question is then one of voltage regulation on the variable frequency system. There are two alternatives: to maintain approximately constant voltage, or to maintain the voltage proportionate to the frequency. For various practical and technical reasons the latter is to be preferred. It may be briefly noted that in an alternating current machine the magnetisation is proportional to the ratio of volts to frequency, or magnetic flux varies as e/f. Hence for any particular load current the excitation required is approximately constant for voltage varying proportionately to frequency, and the operation of the voltage regulator is much the same as for a single d.c. generator, with some measure of compensation for changes in current. The motors, varying in speed with the engine speed, frequency and generator volts, would, in general, meet corresponding changes in load with approximately uniform torque, so that the changes in current due to change in speed would not be great. Voltage regulation in proportion to frequency is therefore relatively simple for the general services power supply, and facilitates the economical design of generators and motors.

In the case of the a.g.p. the requirements would be similar and the advantages of the same type of generator being fitted are obvious. The arrangements for governing speed should aim at holding the frequency within 1 or 2 per cent. so as to be suitable for the standby supply for instruments and radio, but variation within 4 or 5 per cent. would probably be tolerated for this set.

The normal supply to instruments and radio through a special converter or motor generator set will require to be controlled for both volts and frequency within, say, 1 or 2 per cent., and as will be clear from foregoing statements, this largely resolves into accurate frequency control. There are several interesting possibilities to be explored in this matter, and it is likely that the most satisfactory solution will be found in a combination of mechanical speed control and electric or electronic frequency regulation to avoid the complications involved in either a mechanical or electrical method by itself.

In regard to the regulation of supply for lighting, heating, cooking, etc., frequency variation is unimportant. The smaller power demand in military aircraft for lighting would be most suitably met by grouping this with the regulated supply for instruments and radio, while in civil aircraft generous allowance would undoubtedly be required for passenger comfort and morale at landing and take-off and could be controlled by manual or automatic induction regulators or tapped transformers off the variable fre-

quency system. Cooking and heating for passengers and crew could be similarly controlled but with less critical requirements, or regulated thermostatically, on the varying voltage supply.

(*j*) *Distribution of Electric Power*

In considering this important aspect of ancillary services, the conditions to be met in aircraft are rather different from those pertaining to other fields of electrical engineering.

There are two principal methods of distribution applicable, viz., the operation of generators in parallel with all services supplied from the common system, or the independent operation of generators with suitable subdivision of the services and changeover supply arrangements necessary to maintain essential services under all contingencies.

The necessity for a central power switchboard is frequently assumed, but there is very little case for it. This is essentially a derivative from heavy electrical engineering on land, associated with parallel running for minimising idle or underloaded plant and skilled labour in charge of generating plant. It is avoided in the larger warships by the spread of the ring main (all below armour) which is admitted as not feasible in aircraft.

The principal disadvantages, particularly in a military aircraft of a parallel system, are its greater vulnerability, weight and occupancy of space in operationally important parts of the aircraft, together with the extra length of cable runs with consequent weight, pressure drops, worse regulation, risk of breakage or failure of insulation and congestion of wing roots, complication of transport joints and additions to effort in design and production.

Advantages are difficult to find except, possibly, accessibility of equipment for maintenance.

Parallel operation has generally been adopted for aircraft direct current installations up to the present with a common secondary battery. Restricted generator capacities and power/weight ratios have prevented more serious consideration of independent operation, but paralleling cannot be regarded as a satisfactory substitute for an adequate generator capacity since it adds to weight of cables without giving full security against damage to supply, *e.g.*, during attack. Thus in a bomber equipped with several turrets, if one or two generators were put out of action, the remainder on the system would probably be unable to cope with the demands of all the turrets attempting to maintain defence and might therefore in a paralleled system prevent the effective use of any single turret which could be brought to bear on the enemy at the time.

It should be borne in mind in this connection that we are considering only the relative merits of alternative electric distributions which as a class are generally recognised as less vulnerable than hydraulic systems, apart from the effect of engine failure which can be more easily dealt with by alternative electric supply than by an emergency hydraulic system.

The practice of providing two supply cables to turrets is likely to be favoured in large aircraft, and with the trend towards larger generators will enable alternative supplies from independent sources to be exploited. Similar arrangements would be suitable for important flight services, *e.g.*, wing flaps and power-assisted flying controls. For heavily loaded services cables in multiple also offer lower total weight.

In regard to alternating current installations, generators of adequate power will no doubt be available in advance of satisfactory methods of speed control for paralleling. Distribution schemes based on independent generators with alternative supplies for important services therefore are called for. The actual arrangement of such schemes will naturally depend on the layout of the aircraft.

Larger aircraft installations will be most effective when most simple. All major

services (with minor services in proximity or otherwise associated) should preferably be supplied by the most direct or convenient path from the two nearest generators with automatic changeover based on selected preference of generator in the designed layout. For example, port wing flap of undercarriage motors required only at take-off and landing might be run from port outboard generator with the a.g.p. as standby; similarly, outer wing services required during flight (possibly including a turret) would be run from the outer generator with the inner as standby; and fuselage services might be run on the nearer inboard generator with the other inboard as standby, except as determined by the requisite division of loads.

There will, of course, be a certain amount of wiring for control and indication which can be given suitable protection when run to control stations, but a high degree of concentration should be avoided, and auxiliary control points, possibly with plug-in facilities, arranged further out on the run to the services, for example, in proximity to wing roots, to deal with cases of a central control station being shot up or otherwise damaged.

Such an installation would make the best use of dispersal of cables for safety and would enable the panels and junction boxes (where required) to be the more easily disposed, inspected, tested or replaced because of more convenient size.

Standby supply from an a.g.p. (until such time as the extra reciprocating plant would be rendered unnecessary by the use of turbo sets) could be provided by means for plugging in jury leads to a number of selected points at wing roots and in main bays of the fuselage. A number of automatic changeover relays would be required, but these can be of uniform type in few sizes, and the various services would thus be flexibly and independently supplied.

In progressing from present d.c. installations, it is concluded that parallel operation of generators will probably fall into disfavour, except in the case of twin-engined aircraft where the reliability of power supply is lower. At a later stage the parallel operation of a pair of turbo alternators may claim consideration.

(k) Protection of Circuits and Supply

The essential features for protection in aircraft electrical circuits are to minimise the risk of fire, to disconnect cables feeding a short circuit and to maintain power supply to all possible services. The introduction of alternating current systems presents a new set of conditions to be met particularly from the short circuit aspect in which the occurrence of a fault will generally have the momentary effect of reducing the pressure to the services connected, without necessarily causing extensive damage either to the alternators or the distribution system, and in this respect the alternating current system is inherently more safe than the direct current system with its usual secondary battery capable of feeding a large amount of energy into a fault in a short time.

The chief considerations to be kept in mind in determining the means of providing the supply and circuit protection are those of simplicity and lightness, and the system previously referred to in which generators operate independently will contribute greatly to this desired simplicity. In this case it will almost certainly be unnecessary to protect generators against internal faults and only a limited range of circuit-breakers with thermal overcurrent trips will be needed to give protection in the main circuits, this type of apparatus being generally used at suitable control and distribution points to serve the function of main switch as well as protective device. It is visualised in this respect that current ratings of 20, 40 and 80 amperes in circuit-breakers will suffice to meet practically all requirements.

For protection in the larger number of circuits supplying smaller power services to lighting, instruments, etc., a range of fuses with suitable characteristics is proposed. The conditions which such fuses will have

to meet include the ability to open circuit with a high degree of reliability after the momentary peak short circuit current has subsided and before the overloaded cables can reach a dangerous temperature. Moreover, these performances must be achieved under all possible altitude conditions.

The indications, therefore, are that fuses suitably packed with granular material providing rupturing capacities up to that of a 30 kVA alternator, capable of feeding something like ten times this power into a short circuit, will probably offer the simplest solution. It is contemplated that such fuses may in the majority of ratings be accommodated within the dimensions of the present type of low voltage air-filled cartridge fuse, and that this range of fuses may be provided with elements of such sizes as to give the desired ratings which can be selected for the various circuits in relation to the sizes of cable which they comprise.

4. *Actuation of Services*

(*a*) *General Considerations*

The application of electric actuation to aircraft services appears to lie in two broad divisions, those of the small power class and those of larger power. The former comprise the replacement of mechanical controls and manual effort and the provision of automatic features such as cannot be offered by any ancillary power system but electric, while the latter comprise the more important aircraft services which have in the past generally been hydraulically operated. These two classes appear to call for separate treatment.

There will be some cases in which safety requirements will insist upon some form of emergency operation, such as an overriding manual switch to by-pass automatic control, or a manual release to drop an undercarriage by gravity or a local cable to open bomb doors or hand cranking attachment to work wing flaps. These arrangements will naturally depend on the individual design considerations and will affect the method of actuation applied and its system of control.

(*b*) *Small Power Actuators*

The extent to which many secondary services in aircraft could, with advantage, be operated electrically is becoming more evident. The possibilities associated with self-contained electric actuating devices and mechanisms have not hitherto been fully achieved in British practice owing to the lack of apparatus of a sufficiently compact and specialised kind. In larger aircraft the difficulties of operating remote gear mechanically, apart from military damage, are chiefly those of friction, inertia and derangement due to creep and flexure. In small aircraft, distraction of the pilot must be reduced to the minimum in secondary operations, *e.g.*, as by switch or push button, or automatic control. The need for reducing human effort in all types of aircraft is well recognised.

Improvements in the layout with benefits in production and servicing of aircraft are largely dependent on simplifying the means of operation. Given the right sort of actuator, *e.g.*, with self-contained motor, as a unit assembly adapted for ease of mounting and removal, the designer's task is greatly simplified since many of the former problems of finding suitable runs for rods, wires, chains or pipes, with location for brackets, pulleys and levers, are eliminated. The reduced congestion of cockpits so achieved is in itself valuable, but the effects in facilitating production and maintaining serviceability through ease of installation, inspection and replacement are probably greater.

It would be a fallacy to assume that apparatus must be less reliable if power operated by a small motor than if manually moved through cranks, levers, rods or wires. In fact, actuator units can now be made with adequate endurance electrically and mechanically through the development of suitable types of motor for high working temperatures and improved heat dissipation combined with compact form.

In the larger aircraft the weight of

mechanical fittings for many secondary applications is several times greater than would be the case with small electric actuators. Advantage can be taken of the light weight of short time rated motors running at high speed. Up to moderately high powers it will generally be lighter to add electric actuators to the existing ancillary power system than to adopt any other form of operation. Owing to the diversity factor and intermittency of the loads for operations such as fuel cocks, transfer valves and temperature controls, small motor actuators comparable in weight with solenoids offer a method lighter in the overall installation and low in maintenance.

The reduction in overall cost in design effort, planning and production in connection with aircraft secondary services made possible by the adoption of electric actuators, and the scope offered for automatic control of many such operations, are undoubtedly attractive to the designer, especially at the present time. Ease of installation, testing and servicing, and the general measure of effectiveness achieved in performing the variety of services, are among those features which will no doubt be taken into consideration by the user, whether military or civil. General suitability for purpose in relation to frequency or infrequency of operation, compactness and adaptability of actuators, will therefore determine their selection, and are in fact more important than very low electrical consumption or an unduly high standard of mechanical precision such as may involve uneconomic manufacture or replacements.

(*c*) *Major Services*

For the operation of primary services, particularly where large powers are required, it may appear unlikely that self-contained actuators will always form the most suitable method, since this sort of arrangement would mean the substitution of a simple hydraulic jack by a more complex combination of high-speed motor, gear train and screw. In truth, however, while all the complexity of the electrical method can be thus concentrated in the actuator, that of the hydraulic method is distributed over a larger part of the aircraft and has to exist and function in far less convenient conditions. The most suitable arrangement in regard to weight and efficiency will be arrived at by undertaking the design of the aeroplane component or service from the standpoint of electric operation at the beginning rather than attempting the mere replacement of the hydraulic jack.

There is most certainly the need in high power operations to adopt the most efficient mechanical transmission in order to minimise the power and weight of motor, and high speed in the latter is found to give relatively lower weight in spite of higher gearing ratio. Where the screw jack type is adopted it will generally be necessary to incorporate ball bearings between the worm and nut for high efficiency, and old as this idea is, a large amount of new development appears to be going on in connection with actuators for major services.

It is of interest here to note the approximate size of a.c. motor which would serve in a hypothetical case. Assuming a 75,000-lb. aircraft to have two main landing legs of 2,000 lbs. weight each and a nose wheel leg of 500 lbs., and that the mass of the main leg is to be raised 5 feet in retraction in $2\frac{1}{2}$ seconds. With a mechanical efficiency of 50 per cent. using ball bearing jack, each main leg requires a motor of 16 b.h.p. average output for the period retraction, neglecting drag load, either assisting or opposing the motion. A short time-rated induction motor of the type now being developed for this power will be about 4 inches diameter and 6 inches long, running at some 10,000 r.p.m. and weighing about 20 lbs.

(*d*) *Types and Ranges of Actuators*

Actuators may be of linear (*i.e.*, screw jack) or of rotary type, the latter being arranged for slow shaft drives or moderate

speed flexible shafts connecting a number of operating points, usually with a further worm gear and screw jack at each point.

Broadly speaking, there are two principal alternative arrangements for either type. In one the motor is located at the side of the gearbox, usually overhung on its end frame and driving through high efficiency spur gearing with or without a worm reduction stage, according to the required mechanical output. This arrangement is adopted in a range of light, compact units produced in America, as illustrated in Fig. 3. In the alternative, a co-axial layout is adopted, as shown in Fig. 4, usually with epi-cyclic gearing, having a neater outline, but it is doubtful whether the weight could be got down to that of the offset motor arrangement

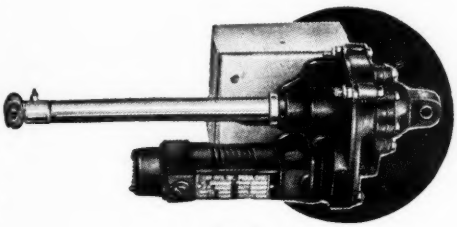


Fig. 3.

for the same performance. A variant of this arrangement is of figure 8 shape, which is convenient for making a short form of jack; the motor and the gearbox form the two parts of the figure 8.

The practical utility of compact mechanisms of these types are widely recognised, and for many aircraft applications it is only necessary to couple the jack by its thrust points to fixed and moving parts of the airframe. It is desirable to achieve a degree of standardisation particularly in regard to mounting arrangements and of overall limiting dimension for certain types and applications, and this aspect is now being given consideration by some makers.

There is much to be said for being able to assemble stock components of actuators of the same make in various combinations to meet diverse needs, while aiming at common mounting particulars among different makes.

Some particulars of current and proposed American and British actuators are shown in the accompanying tabulations. These particulars give an indication of the need for reasoned planning of a suitable range of actuators, and there is clearly much to be done in joint study and mutual education between aeronautical and electrical engineers to achieve the most effective solution to the various actuation questions.

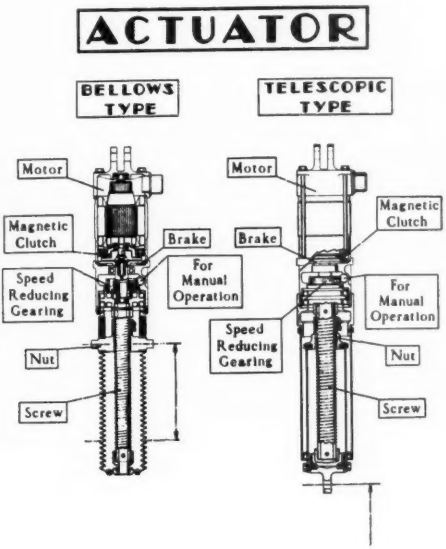


Fig. 4
Heavy Duty Actuator.

Standardisation will not meet all requirements, but economic manufacture and use and general availability will no doubt be assisted if preferred sizes, ratings and performance can be adopted.

It will be noted from Table 5 and Table 7 that American small power actuators have already been widely introduced, and that attention is now being given to applications up to the largest conceivable loads. If a high mechanical efficiency, say 50 per cent., is obtained, *e.g.*, with a ball bearing screw

TABLE 5

Performances, etc., of Actuators in American Applications

Type	Normal		Maximum		Weight (lbs.)	Motor		Gear ratio	
	Load	Speed	Load	Speed		Output	Wt. (lbs.)		
Linear	300 lbs.	18 ins./min.	500 lbs.	11 ins./min.	3.3	35 watts	1.0	190	3.6 in. stroke
,,	1000 ,,	15 ,,	2200 ,,	9 ,,	6.0	100 ,,	2.0	204.8	4.6 ,,
,,	1500 ,,	43 ,,	3250 ,,	18 ,,	14.7	500 ,,	5.56	86.6	9.5 ,,
Rotary	1.5 lb.-ins.	1300 r.p.m.	2 0 lb.-ins.	1200 r.p.m.	5.75	30 ,,	1.7	6.84	For flexible shaft drive
,,	4.0 ,,	1600 ,,	8.0 ,,	900 ,,	6.0	100 ,,	2.0	6.84	,,
,,	5.0 ,,	1250 ,,	12.5 ,,	750 ,,	6.6	120 ,,	3.43	7.94	,,
,,	10.0 ,,	950 ,,	20.0 ,,	625 ,,	5.85	120 ,,	3.43	10.6	,,
,,	15.0 ,,	1250 ,,	40 ,,	700 ,,	7.37	300 ,,	4.39	7.94	,,
,,	100 ,,	14 ,,	150 ,,	10.5 ,,	4.2	30 ,,	1.7	767	Splined shaft drive
,,	225 ,,	3.2 ,,	400 ,,	1.7 ,,	3.8	30 ,,	1.7	3500	,,
,,	260 ,,	11.5 ,,	580 ,,	9.8 ,,	4.62	100 ,,	2.0	767	,,
,,	600 ,,	3.92 ,,	1000 ,,	2.56 ,,	4.62	100 ,,	2.0	3065	,,

The above are specific applications in regular manufacture. Linear types are designed for mounting by shackle bolts at thrust points, rotary type having mounting base or through belts in gear case. Weights include worm-driven limit switches, and motor weights include combined clutch and brake.

TABLE 6

Performances, etc., of Actuators in Current British Applications

Type	Normal		Maximum		Weight (lbs.)	Gear ratio	
	Load	Speed	Load	Speed			
Linear	50 lbs.	14 ins./min.	100 lbs.	10 ins./min.	4.6 lbs.	12 T.P.1 and single gear	3 in. stroke
,,	300 ,,	4 ,,	600 ,,	2.6 ,,	5 ,,	12 T.P.1 and double gear	,,
,,	73 ,,	7.8 ,,	125 ,,	4.6 ,,	4.7 ,,	26 T.P.1 and single gear	,,
,,	300 ,,	1.8 ,,	600 ,,	1.3 ,,	5.1 ,,	26 T.P.1 and double gear	,,
,,			80 ,,	10 ,,	1.2 ,,	864	2 in. stroke
,,			3500 ,,	4.3 ,,	6.5 ,,	6455	3 in. stroke. Max. efficiency 17% at 2500 lbs.
Rotary			800 lbs./ins.	0.3 r.p.m.	5 ,,	8000	270° movement
Linear	1500 ,,	9 ,,			5 ,,	8 T.P.I.	3 in. stroke. Motor as mass balance for tab
,,	3000 ,,	2.4 ,,					3 in. stroke
,,	250 ,,	5 ,,					$1\frac{1}{2}$ in. stroke trim tab
,,	500 ,,	3 ,,	700 lbs.	3 ins./min.	5.75 ,,	9 T.P.I.	
,,	750 ,,	7 ,,	1500 ,,				3 in. stroke rad. flap
,,	60 to 270 lbs.	$1\frac{1}{2}$ in. stroke in 5-9 secs.					Hot air flap
,,	160 lbs.	21 ins./min.					$1\frac{3}{4}$ in. stroke: hot air flap
,,	100 ,,	12 ,,					2 in. air cleaner
,,	25 ,,						3 secs. supercharger gear ch.
,,	600 ,,	12 ,,					3 in. stroke oil rad.

The above are specific types in manufacture or prototype. Various others are in course of design.

and good gears, the motor for the largest load shown in Table 7 is only 20 h.p., while about 24 h.p. would be needed for the largest load in Table 8 in view of the higher speeds aimed at in British practice. The shorter time of duty will, of course, tend to keep down the relative motor weight if carefully chosen for the correct duty cycle.

TABLE 7

American Proposed Standard Range of Jacks

Working load (lbs.)	Static load (lbs.)	Stroke (ins.)	Time (secs.)
1,333	4,000	12	10½
2,100	6,300	14½	13
3,333	10,000	15	15½
5,333	16,000	17	19
8,333	25,000	19	22½
13,333	40,000	21	27
21,000	63,000	23	31
33,333	100,000	25	35
53,333	160,000	27½	40
83,333	250,000	30	45

TABLE 8

M.A.P. Range of Jacks Under Development

Working load (lbs.)	Speed class (secs./in.)	Stroke (ins.)	Time (secs.)
40	3	3	9
160	8	3	24
630	8	3	24
1,250	6	4	24
2,000	6	4	24
3,150	1	11	11
5,000	2	12	24
8,000	½	12	6
20,000	¼	20	5

NOTE.—All the above are being designed with a.c. motors and the small sizes with d.c. alternatives for possible interim uses.

Table 9 gives a variety of services in current British aircraft design, many of which have been found practicable to operate electrically, while the others are being considered for similar treatment.

While there appears to be considerable diversity in the characteristics and performances called for, closer examination reveals that over a wide range of the actuators shown in Table 9 there can be a large measure of common design on the motor and primary reduction gear. For example, the working loads ranging from 2,000 lbs. to 10,000 lbs. at the speeds required could be operated with only two sizes of motor for ten styles of actuator, so that the rotary portions of the gearboxes forming the body of the actuator can be made up of a number of common parts, with a variety of screw output stages, to meet the individual requirements.

TABLE 9

Selection of Actuators for Specific Applications

Working load (lbs.)	Speed class (secs./in.)	Stroke (ins.)	Function
60	15	3	Air valve
60	4	6	Oil cooler
100	4	6	Oil cooler
100	2	6	Air intake
120	15	3	Ventilating
200	15	3	Cooler
300	12	6	Oil cooler
300	½	10	Jack
400	45	2	Trim tab
400	15	1	Trim tab
400	2	6	Tail wheel
600	5	3	Oil radiator
1,000	10	1 & 8	Oil cooler
1,000	1	3.5	Dive rec. flap
1,600	1½	6	Tail wheel
1,600	½	4	Dive rec. flap
2,000	3	4	Rad. shutter
2,000	⅔	6	U/c doors
2,500	½	6	Air brake
3,600	1½	2.3	Air brake
4,200	1	6	Wing flap
4,200	.8	5	Wing flap
5,000	1	5	Nose wheel
5,000	½	10	Chassis
8,000	2	6	Wing flap
10,000	1½	7	U/c
10,000	1	5	U/c

(e) *Position Indicating, Limit Switching and Braking*

These functions constitute important features in the design and application of electric actuators, and will inevitably result in differences of technique both from the point of view of manufacture and installation

design. In some services it is essential that position indication and limit switching of high accuracy is achieved, and this will generally require that the micro switches or other device are fitted on the airframe components instead of being embodied in the complete actuator mechanism. Where, however, it is possible to adopt the self-contained arrangement there will be obvious advantages from the point of view of wiring, pre-setting, etc. It is also very probable that more consideration will be given in the future to the use of position indicating signal lamps as a simpler alternative to the use of potentiometer type transmitters, particularly in conjunction with the development of alternating current systems.

In connection with the use of high-speed motors, the practice has grown up in America of the use of a combined magnetic clutch and brake arranged so that when power is cut off the clutch is de-energised, thereby enabling the high-speed rotating parts freely to dissipate the stored energy, while at the same time a brake surface is engaged to arrest the mechanical slow-moving parts with the minimum overrun or creep. This method has a lot to recommend it in the ability to use light apparatus with the minimum risk of mechanical overload which would be accompanied by the necessity for high stressing of various parts and, in general, is likely to recommend itself more than the possible alternative of allowing the actuation movement to continue to the point of jamming, although there are specific cases where this practice might conceivably be adopted with robust squirrel cage motors of limited stalling torques. The applications visualised of electric actuation with simple robust high-speed motors will therefore enable a variety of mechanical conditions to be met.

(*f*) *Electro-Hydraulic Possibilities*

As an alternative to the use of high ratio gears between the lightweight motor and the point of movement of the airframe component, the use of a local compact hydraulic system will naturally receive a good deal of attention. It would, in many cases, be feasible to operate a high-pressure pump at fairly high speed with a simple one-stage gear reduction from the high-speed motor and to locate such an electric pump conveniently close to the point of application of power so that there will be the minimum of high-pressure oil pipe line and accessory fittings while enabling the lighter weight of compact high-pressure cylinder jack to be used on the moving parts.

Such an arrangement would enable full advantage to be taken of the simplicity and weight-saving associated with the generation of all the ancillary power in the lightweight high-speed alternator and avoiding the troubles commonly associated with hydraulic pipe lines through the aircraft. Such an arrangement would also clearly be preferable to a combination of electric control and hydraulic operation in which the main system remained that of hydraulic transmission combined with remote electric control through solenoid operated valves.

Similarly, there is scope for small power electro-pneumatic operations in which, for example, doors, ventilators, shutters, etc., can be push-button controlled with a minimum of mechanical gear to fit and maintain, particularly where the operating force needs to be applied at several points and the motion smooth and free from jamming without being fast.

(*g*) *A.C. Motors*

A special range of 400 cycles 3-phase squirrel cage induction motors is being developed for aircraft services. These machines will be standardised as consisting primarily of stator and rotor units suitable for building in to the housing of the gear which they are required to operate, and also with standard square end frames so that a degree of interchangeability will be attainable as regards pairs of stator and rotor units, while as between one make and another there may be differences in respect of rotor diameter, air gap clearance, windings or

other particulars. The motors will be 4-pole design having working speeds below 12,000 r.p.m., depending upon the degree of resistance incorporated in the windings so as to provide a variation in regard to the torques required for starting, stalling and running.

The notable features of such machines are the absence of any form of rubbing contacts such as brushes with commutators or slip rings, the provision of durably impregnated stationary windings and a rugged type of solid rotor in which the conductors are metal bars embedded in the iron. Suitably designed, these motors will be virtually indestructible, with no maintenance beyond that required for the inspection or changing of ball bearings.

The applications for which these motors are intended indicate a preference for machines of relatively small diameter in relation to their length, particularly in the case of very short time ratings in which cooling is a matter of surface dissipation rather than ventilation.

For convenience in application, these motors will be made in progressive standard sizes designed to give the maximum power output under various conditions, and the following are estimated values of power expected as continuous rating for 100°C. temperature rise, with suitable incombustible insulation and fitted with self-cooling fan for open ventilation from machines of core length equal to stator outside diameter, and for machines of shorter type.

Continuous rating, h.p. (estimated):	$\frac{1}{8}$	$\frac{1}{2}$	$1\frac{1}{4}$	$2\frac{3}{4}$	$5\frac{1}{4}$	10	16
Motor diam. (length = core O/d.): ins.	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$
Motor diam. (length about $\frac{2}{3}$ core O/d.): ins.	—	—	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	5

It is, however, to be expected that these sizes will be made to develop much greater powers for very short times, in which cases the ventilating fan may be omitted. For actual cases of continuous operation, which are relatively few in aircraft, the shorter motors will enable more effective cooling to be achieved and are expected to have a life of some 4,000 hours. These will have the lowest possible resistance rotors consistent with starting torque equal to full load torque, and such motors will have an efficiency about equal to direct current machines of equivalent rating.

For short time duty motors, where greater starting and stalling torques are required, the resistance and, therefore, losses will be somewhat higher, but this is acceptable in such cases.

(h) Electric Servo Applications

From the class of electric actuators previously considered in which power is applied in a direct manner by manual or automatic switching there will naturally arise a more advanced technique for servo mechanism to assist operations normally performed manually and enable the much greater loads on flying controls encountered in large and faster aircraft to be accepted in general without fatigue to the pilot, and in many cases loads beyond his physical powers, can be thus controlled.

The term "boost" has been loosely applied in such cases, *e.g.*, where hydraulic or aerodynamic assistance has been employed. It is preferable, however, to adopt the term "electric servo" owing to the growing number of different meanings already associated with "boost" in aeronautical engineering, apart from others long established in electrical engineering.

In regard to main flying controls the present practice is to arrange for a proportion of the load on the levers of aerofoils to be returned on to the pilot's controls so as to preserve "feel." This practice gives rise to a measure of complexity in the mechanical or electrical apparatus used. It should be possible to adopt a more simple arrangement of progressive reaction to the stick or rudder bar movements, such as a calibrated spring loading in combination with a pressure switch or potentiometer regulator controlling the power assistance. In the larger aircraft

particularly of non-military type, such an arrangement would probably commend itself to operators for weight-saving and simplicity in installation and maintenance. In regard to its functioning in flight, the effect would be similar to that of the "formation stick" recently introduced in certain American aircraft as a two-axis hand override to the auto-pilot which acts as the servo unit.

It is considered most likely that the information which could be obtained from a more intensive degree of test flight instrumentation in this country, particularly the correlation of recorded stick forces and aerodynamics loads on control surfaces under various conditions of flight control, would give a better indication than is now available of the extent to which the servo system should be simplified on the lines indicated.

For the operation of wing flaps, trim tabs and similar services, relatively simple pre-selection or follow-up arrangements are required. With lack of experience of these systems position indicating independent of control is at present generally required, but it is to be hoped that confidence and familiarity in the use of electric follow-up or pre-selection will enable further simplification to be effected by omitting the separate indicating circuits and instruments.

In large aircraft, the flexure of wings necessitates flaps being articulated with separated actuators, and it will in such cases be required to synchronise the movement of the several sections. Electrical means have been found most convenient for this purpose even when hydraulic actuation is used. The development of more suitable motor actuators for the a.c. system is therefore calculated to simplify this service by providing closer control of the operation.

Electric servo will no doubt also be employed in large aircraft in arrangements to give a suitable measure of stability in flight where more power is required than can be efficiently obtained by aerodynamic assistance. Such a case might be that in which a tab is arranged with a cavity in the aerofoil in front of its axis and a plane element carried opposite the tab surface so as to divide the cavity into two chambers which are connected respectively to the suction or upper and the pressure or under sides of the aerofoil by small air pipes so as to admit differential pressures on the plant element, thereby inducing a controlling or stabilising force on the tab. It would then be feasible to introduce an electric servo actuator applying power to the tab and controlled by a pressure switch or a set of contacts operated by the counter plane in the cavity as referred to above, which could thereby be considerably reduced in size so as to improve the general design of the aerofoil, besides increasing the effect of the tab.

The remote operation and grouping of engine controls comprise another direction in which electric servo can be adopted to overcome present difficulties in installation operation and maintenance. Various forms of single lever control have been proposed, including balancing potentiometers, follow-the-pointer method with "Type M" positioning motors, and synchronised signals between cockpit and power unit with engine oil pressure used for the actuating power. The most popular method will probably be that one which is found to offer the simplest means of setting itself to the selected cruising position in the event of any failure in the remote control.

With the availability of the 3-phase power system, the use of power selsyns naturally suggests itself, but there will need to be further development for combining on the transmitters the various factors which are required to control the throttle settings. It seems desirable that this computation, together with any necessary relative adjustment as between engines, should be effected in a master controller near the cockpit or the engineer's station from which the fuel metering would be passed to each engine. For failing to safety a normally closed valve could then be used to allow an engine oil

piston to move the throttle to the cruising setting on removal of the current, and the failure of engine oil should in turn permit a cut-off of fuel or ignition.

It is hoped that collaborative development by the engine and equipment makers on these lines will produce the simplest and most reliable method of single lever control, and that similar joint consideration of aircraft services will provide the most suitable electrical operation.

(*j*) *High Ratio Power Amplification*

In recent years developments have taken place in quick response electrical systems having a high ratio of output power to input control, typical methods being known as the "Amplidyne" or the "Metadyne." Up to the present, aircraft applications seem to have been confined to the operation of gun turrets, but there appears to be no reason why this method might not be used for other special servo requirements where quick, accurate and powerful control is needed. The special generator employed has its main excitation built up by armature reaction through changing the position of the magnetic and electric axis from that of normal practice to one at an electrical right angle and greatly reducing the magnitude of the basic excitation controlling the armature current and magnetic field.

Naturally the use of such a system requires the retention of commutators and brushes, which involves special consideration of high altitude conditions, particularly for any continuous or frequently operating service. In the a.c. system he generator would be driven by an induction motor, and it may be found possible to develop a brushless a.c. generator giving some of the characteristics of the power amplification scheme.

5. *Entry of Electronics*

As in many other fields of development, this branch of electrical engineering has an important contribution to make in aircraft equipment, quite apart from the uses of radio and other communications. Electronic devices and methods are adaptable in many ways as sensitive amplifiers of minute electrical changes which can be used to combine any number of factors or conditions required to determine the setting of controls to meet these conditions, as well as to measure or record them.

Typical applications include the various forms of electric auto-pilot, the exhaust turbo supercharger regulator in which the motor-operated waste gate is regulated by a combination of potentiometers, feeding signal voltages into a common amplifier as determined by the boost selector, speed and acceleration governor and induction manifold pressure; and similarly for turret control in which electronically built-up currents or potentials are used to control the excitation of the high ratio power amplification of the amplidyne type.

Smaller and simpler electronic equipments are being added for fuel contents measurements, ice-layer detection and other purposes. The ability to use apparatus of this sort in static applications as opposed to delicate movements will be widely appreciated in aircraft, and there will be many cases in which some physical property employed to detect or measure an important condition in flight can be amplified to the necessary level of sensitivity and robustness by electronic means.

The use of such methods will be much encouraged and assisted by the adoption of the aircraft a.c. system which will dispense with the growing number of special inverters hitherto required on d.c. supplies.

6. *Lighting*

(*a*) *Fluorescent Discharge Lighting*

The introduction of 400 c/s supply at 120 volts between each line and the neutral point (as given by the 208-volt 3-phase system) is eminently suitable for improved lighting sources of the fluorescent gaseous discharge type. Among the main features applicable to aircraft use of such lamps are (*a*) high efficiency in conversion of power into light, (*b*) a convenient low intrinsic brilliancy

through much greater spreading of the light source than is possible with filaments, (*c*) the ability to use such tubular lamps in close proximity to occupants of the aircraft without glare or shadows, and with a minimum of dispersive fittings, (*d*) ability to provide natural daylight or various decorative colour effects and various convenient shapes of lamp tubes to suit difficult conditions of cabin layout, (*e*) the absence of fragile filaments giving a life expectancy of some 2,000 hours as the lamps are practically unaffected by vibration.

It has been found that operation on 400 c/s is superior to that on the lower frequencies in common use as regards light output at low temperatures and starting characteristics. Lamps of, say, 18 inches and 24 inches length will generally be found convenient in aircraft lighting and are suitable for connection to the 120 volts a.c. circuit. Larger lamps, if required, could be connected at 200 volts, and in either case the starting condensers and stabilising chokes needed will be small and light as designed for 400 c/s frequency.

Figs. 5, 6, 7 and 8 show a recommended circuit arrangement and the approximate operating characteristics on 400 c/s supply with bare lamp tubes, with close-fitting hood type reflectors and with an enclosing tube of clear glass for cold situations. These particulars are quoted from "Electrical Engineering" (Transactions A.I.E.E.), October, 1944.

(*b*) *Glow Lamps*

The small, filament-less, gas discharge lamps which will in future be made in ratings of 1 or 2 watts, and fractional wattages, are particularly well suited for indicator use on 120 volts as they consume very little power, are extremely rugged and long-lived, avoid the need for transformers, and by glowing equally on both electrodes on a.c., avoid the troublesome brilliance of small low voltage filament lamps on dash panels. On a wide range of normal and low ambient temperature they have been found to have negligible change in light output and operating characteristics.

(*c*) *Continued Use of Filament Lamps*

There will, of course, be many instances in aircraft lights for which filament lamps are essential, such as exterior points where accurate cut-off and other directional characteristics are required. For landing lamps of high power it will probably be preferred to use lamps designed for medium pressure a.c. direct, but for low power lamps the use of small transformers or line impedances at wing tips or other remote positions is indicated to make use of the combined advantages of strong, efficient, compact, low voltage lamps and smaller, lighter cables at the higher pressure.

In regard to cockpit lighting, recent experience and developments have shown the great value of a combination of orange or red light with the fluorescent illumination of instrument panels, the basis for which has been treated by Mr. E. S. Calvert, of R.A.E., Farnborough, in a paper presented at the A.I.E.E. Los Angeles meeting in September, 1944 (A.I.E.E., 44-212).

7. *Installations*

With all or most of its ancillary services electrically operated, the modern aeroplane can derive little from the automobile for its electrics, as was once the case. It will, moreover, be clear that with the advent of the new outlook on alternating current a particular field of engineering is opened in regard to aircraft electrics which must have a treatment unfettered and prejudiced by an established practice in other directions in order to achieve the desired level of simplicity, general suitability for purpose, and minimum of maintenance.

It will be of some value here to set down a summary of the most important features which must be combined in the selected aircraft electrical installation, and they have been cited in the following order in a paper by Boice and Levoy, printed in the Transactions of the A.I.E.E. for June, 1944:—

"1. Maximum reliability under all conditions encountered in operation.
   (*a*) Reliability of equipment such as motors and generators.
   (*b*) Service continuity should be maintained automatically even during faults or emergency conditions, in so far as is possible.
   (*c*) Minimise hazard to operating personnel, aeroplane and equipment.

2. Minimum weight.
   (*a*) Minimum installed weight.
   (*b*) Maximum efficiency (fuel economy).
   (*c*) Minimum additional aerodynamic drag for cooling requirements (fuel economy).

3. Minimum space requirements.

4. Simplicity.
   (*a*) Ease of operation.
   (*b*) Minimum training time for operating and maintenance crew.
   (*c*) Ease of maintenance in field.
   (*d*) Rapid and accurate checking in field.
   (*e*) Minimise spare-part requirements.
   (*f*) Ease of installation.
      (1) Initially.
      (2) Replacement parts.

5. System should not interfere with the performance of the aeroplane or its equipment in any way, or at least as little as possible.

6. Satisfactory life of all component parts.
   (*a*) Minimum frequency of replacement.
   (*b*) Minimum frequency of overhaul.
   (*c*) Minimum frequency of maintenance.

7. Least cost in man-hours and money.

8. Utilised existing designs of aircraft accessory equipment as far as is practical."

—from which it is concluded that the 208/120 volts, 3-phase, 400-cycle system appears to be a particularly happy choice for aircraft from all points of view considered.

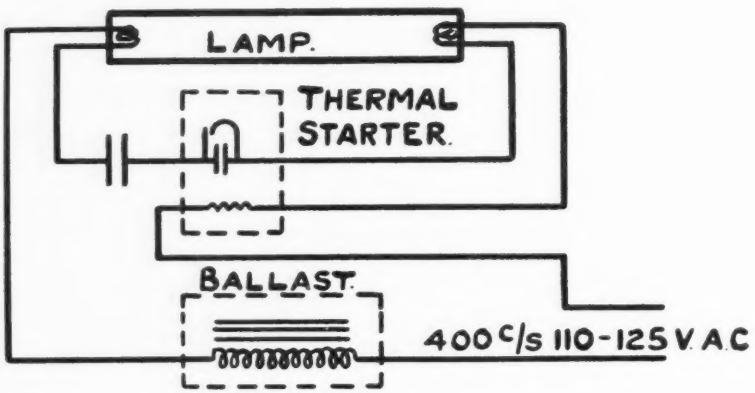


Fig. 5
400 Cycle Circuit to provide dependable starting of Fluorescent Lamps at Low Temperatures.

It is inevitable that the selection of this system will have some effect in determining the best method of wiring the aircraft. Considerable progress has lately been made in the direction of a standard wiring system, and particularly in the adoption of mechanical methods of connecting the ends of cables, thereby eliminating soldering. This improvement will avoid the embrittlement of cables

at the entry of connections where it is important that flexibility should be maintained, as well as removing possible sources of corrosion, etc., through the occlusion of flux vapours and other foreign matter.

It would appear highly probable that there will be further development in the use of bunches of single-core cables in preference to the heavier and less convenient multi-core cables, and, with the acceptance of higher working temperatures made possible by the higher voltage system, the introduction may be expected in this country, as in America, of special aircraft cables using glass and cellulose coverings which will be virtually non-combustible and at the same time smaller and more efficient in cooling than those to which we have been accustomed with rubber or poly-vinal coverings.

Further improvements will no doubt also be made in the accessory fittings for terminating and connecting wiring, particularly in the reduction of the number of component pieces included in present designs. It is becoming recognised that the complete wiring installation is an important component of the aircraft, constituting, as it does, the nerves and arteries of the power system. The system must, therefore, be designed for ease of manufacture, installation in sectional parts of the airframe at the appropriate stages in production, ease of testing, both functionally and for insulation, in building and in service, and, particularly in the case of military types, for accessibility for alterations and additions, while at the same time being afforded every possible protection by the aircraft structure.

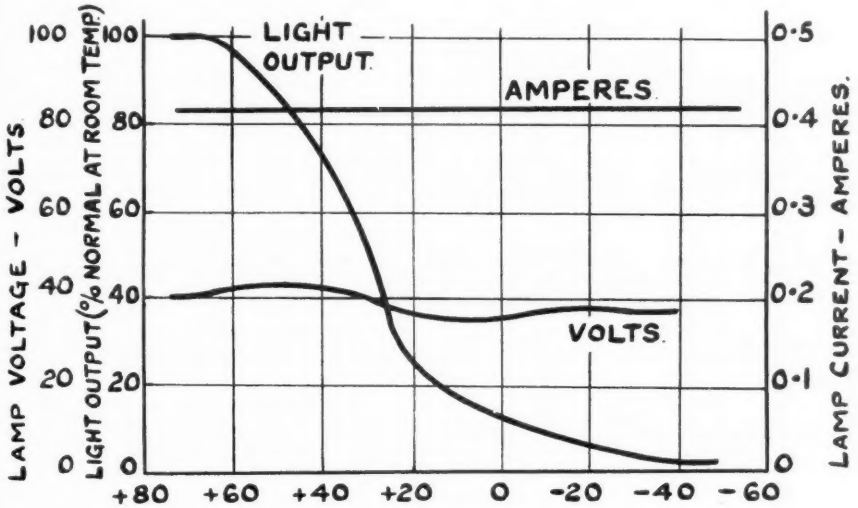


Fig. 6

Temperature—Degrees Fahrenheit. Lamp Tube bare, for normal Ambient Temperature. 400 Cycles, 118 Volts.

With the great reduction in the sources of electrical interference with radio arising from the adoption of the alternating current system, there will no doubt be a greater encouragement for the use of all-insulated methods of wiring in preference to metal shroudings.

8. *Outline of Recommended System*

Having reviewed the interesting new possi-

bilities in regard to lightweight a.c. equipment and the principles underlying its use in the aircraft ancillary services, let us consider the outline on a recommended system for an aircraft of medium size.

Assuming four power units of 2,000 to 2,500 h.p., the electrical power would be supplied from four main engine-driven 12 kw. alternators each with its auxiliary drive shaft and speed increasing gear arranged for bulkhead mounting, each alternator with its gear weighing about 50 to 65 lbs. according to type and speed, and taking the place of the present auxiliary gearbox of each power plant with the various accessories. An auxiliary generating plant also of 12 kw. rating would normally be carried, weighing about 150 lbs., and there would, of course, be no accumulator for power supply, but a small battery, probably of the Alkaline type, would be included to operate fire extinguishers, etc., and possibly to provide primary excitation to the a.g.p. or to any main alternator if required.

Engine starting may be effected either by plain motor cranking, differential-inertia cranking or cartridge firing, as in present practice, with the possible future alternative of the alternator being developed additionally as a starter, and mounted on the engine in conjunction with a flywheel and engaging gear.

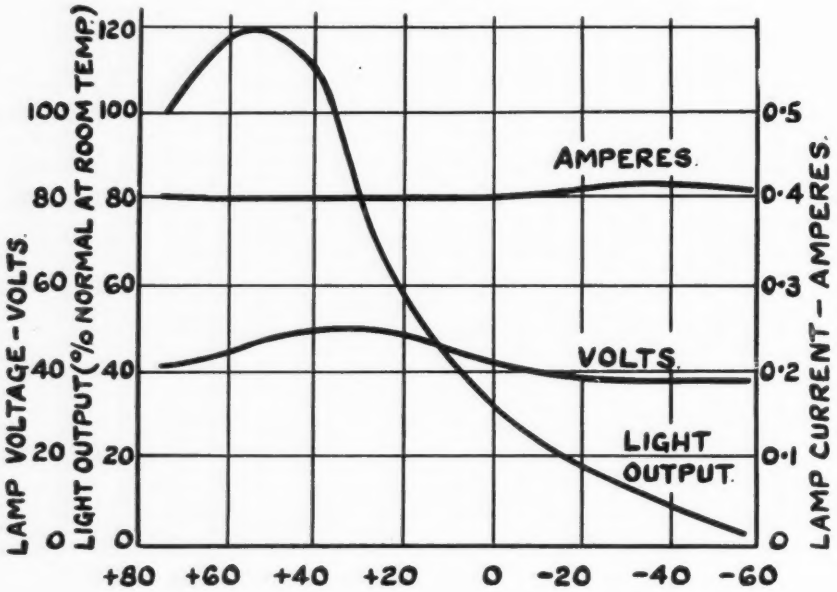


Fig. 7

Temperature—Degrees Fahrenheit. With close-fitting Reflector.
400 Cycles, 118 Volts.

All the services would be electrically powered, although it may be required, for production or other reasons, that motor-driven hydraulic pumps be employed to work high-pressure undercarriage jacks with a compact local pipe system.

The principal services and suitable groups of similar loads would be connected through remote-controlled contactors or circuit-breakers to the nearest or first selected main

alternator with automatic changeover to the nearest selected main alternator, or in certain cases the auxiliary alternator, for standby against engine failure.

The constant frequency converter for supplying to all the important instruments, radio and lighting would be supplied from either of the inboard main alternators as selected with automatic changeover, and the auxiliary alternator would be arranged as the alternative steady 400 c/s source. Gyro instruments would most probably be electrical and included in this service, but any of the suction type retained would be run from a motor-driven vacuum pump associated with the instrument panel.

Armament services would naturally be divided amongst the various generators in accordance with operational requirements and having regard to the needs of flying services, while heating loads would thus be split up so as to balance the loading of the alternators for the various appropriate conditions of flight, such as warming up, taxiing, climbing and cruising.

In general, the recommended principle would be to supply loads and services in the most direct manner from the nearest generator with the maximum of subdivision for weight-saving on cables.

9. *Conclusions*

It will be seen that in the last few years the all-electric aeroplane has been realistically conceived, and while much still remains to be brought forth into being, the stage is now set for the ensuing phase of aircraft design to adopt and take advantage of the simplicity, ruggedness and fitness of new a.c. electrical equipment which this country can produce.

It is appropriate here to refer to two milestones which mark the way to the a.c. all-electric aircraft of the next vintage. One is

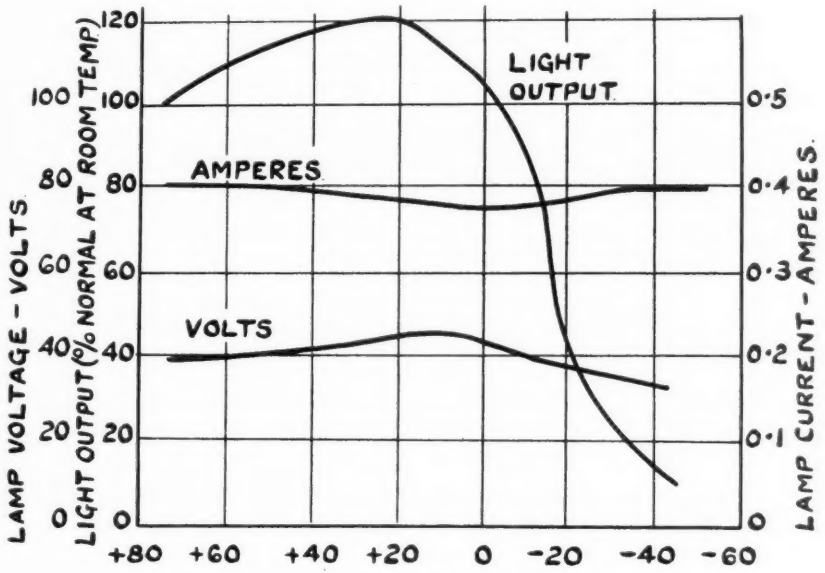


Fig. 8

Temperature—Degrees Fahrenheit. With enclosing Tube for Cold Situations. 400 Cycles, 118 Volts.

the highly successful operation and maintenance experience gained with electrics in the heavier bombers during this war, and the other is the preliminary essay in an aircraft a.c. system for the Shetland flying boat. While in the first case there is beyond question some scope for refinement of design leading to greater simplicity, weight reduction and more compact higher power operation, and in the second the need to recognise the greater efficiency of generating electric power from the main engines during flight and to subdivide the service loads, yet these cases form a good basis on which the development of a complete system can proceed.

In order to ensure the best results in the shortest time, there is everything to be said for the official policy, lately in evidence, of organising the development of the new equipment collectively by a few electrical firms of standing and resources, and if this plan can be augmented by a similar treatment of the engineering of complete new aircraft, type by type, by association of electrical engineers with aircraft constructors, and a measure of exchanging of certain common items of equipment among those undertaking the development, then it is felt that the way has been opened to put this country ahead in this important stage of aircraft and electrical engineering progress.

10. *Acknowledgments.*

Finally I wish to acknowledge the great contribution to this subject which has been made by the investigations of Mr. Neville at the M.A.P., whose copious report has given calculated confirmation to many of the conclusions reached, and has laid the foundation for the development in this country of the system I have put before you. I have to thank The English Electric Company Limited for permission to present this paper, and various members of the M.A.P. establishments and others, for information supplied, which I have used in its preparation. and also to make mention of the varied contributions from a large number of American Electrical and Aircraft Engineers at Conventions held during the past year.

DISCUSSION

CAPTAIN J. LAURENCE PRITCHARD (Secretary of the Society) presided during the discussion, at the request of the President, who had to attend another meeting.

Mr. G. H. DOWTY (Dowty Equipment Co.: Fellow) made the following contribution to the discussion through Mr. R. F. Hunt (Dowty Equipment): —

The paper indicated the vast scope for improvement in aircraft electrical accessories, but it would appear that electrical equipment had not received the same intensive specialised treatment as other aircraft accessories.

Unfortunately, when referring to hydraulic power systems the lecturer had made statements which could give rise to misunderstandings.

Mention had been made of the simplicity of the hydraulic jack compared with the complex electrical actuators, but the lecturer then stated that hydraulic systems were distributed over a large part of the aircraft and must function under far less convenient conditions. On examination, it was obvious that, if electrical methods were to replace hydraulic actuation, then the electrical system must likewise be spread over the aircraft and must operate under exactly the same conditions as hydraulic systems.

Comparison between electrical and hydraulic actuators shows the much greater complexity of electrical actuators. Hydraulic jacks had only one working part, and were so simple that they could be designed and manufactured in a mere fraction of the time required for their electrical counterparts. In order to achieve economy in the manufacture of electrical actuators, efforts were apparently being made to standardise a range of jacks. Table 7 set out some American proposals in this direction. The varying requirements for jacks, such as working load, stroke, free

length of unit, end fittings to pick up with the aircraft constructor's attachments, and space limitations, made it practically impossible to lay down standardised jacks unless the accessory manufacturer hoped to induce the aircraft constructor to design an aeroplane around his components.

Another point brought out in the lecture was that for a given power output, the weight of electrical generators was much greater than the equivalent hydraulic pumps, and they were certainly more costly.

Recently an official of M.A.P. stated that an American visitor to this country had complained of the inefficiency of American hydraulic systems. If hydraulic systems were proving troublesome in America, that argument did not hold good in this country, where hydraulic systems have been most reliable and have given trouble-free service on most production aircraft.

The lecturer made a case for the use of electrically driven hydraulic pumps as a means for reducing the length of pipe-lines. This alternative had been considered, but it must be borne in mind that in high pressure hydraulic systems the weight of pipe-lines was comparatively small, whereas in the system proposed there was considerable extra weight in the electrical generator, motors, and gear boxes.

The lecturer stated that in the operation of such units as fuel cocks, transfer valves, etc., small motor actuators offered a lighter installation and lower maintenance than solenoids. In view of the low weight and compact size of present solenoids, he doubted if this statement was justified, since with any motor there must be reduction gearing and means for stopping the motor, all of which caused complications.

The lecturer stated that it was essential for the design of electrical equipment to be considered at the time the aeroplane was designed, rather than attempting the mere replacement of hydraulic jacks. There was no doubt that the application of hydraulics was more flexible than that of electrics and the design of hydraulic accessories generally required little consideration in the early stages of the design of the airframe.

The question of emergency operation had been lightly glossed over. The factor was so important that much more careful consideration would have to be given to it by the electrical accessory manufacturers if they were to provide such simple and low cost equipment as that used on hydraulic systems. Certainly hand cranking will be unacceptable.

He saw no evidence that electrical actuation of undercarriages and wing flaps could compare with hydraulics for simplicity, low weight, low cost, or ease of maintenance.

The lecturer had given no weight figures for complete electrical power installations. The paper largely dealt with the hopes of the electrical engineer rather than the recording of achievements.

On a well-known large aircraft of 75,000 lb. weight, the complete hydraulic system for the actuation of undercarriage, wing flaps, fuel jettisoning, hot air intake jacks, inclusive of engine driven pumps, control valves, reservoir, all pipe lines, weight of oil, and including emergency operating systems for undercarriage and wing flaps, weighed 283 lb., or .375 of 1% of the gross aeroplane weight. We had seen no equivalent electrical equipment for a similar size of aircraft that came within twice this weight.

The aircraft constructor will eventually use the equipment which was most economical, and he felt satisfied that while electrical equipment could play an important part in future aircraft designs, hydraulics would remain the most satisfactory and efficient method for actuating heavy duty power services.

Mr. H. G. CONWAY (Aircraft Equipment Ltd.: Associate Fellow): Although concerned with hydraulic systems, he had certain electrical sympathies. Recalling that Mr. Dowty had quoted 280 lb. as the weight of a complete hydraulic system, he said that the Halifax had had two different hydraulic systems, each of which had weighed about 600 lb. Of

that, more than 50 per cent. had consisted of pipes, mountings and bits and pieces not associated with the main actuation.

By far the greater percentage of the trouble experienced with modern hydraulic systems—and they did give trouble sometimes—was due to the pipes and to the fact that the pipes carried fluid in them. He suggested that, by introducing a mixture of electrics and hydraulics, well over 100 lb. of the total weight of 600 lb. could be saved, and that improved reliability would be effected also. Merely to say that hydraulics were better than electrics was rather to knock one's head against a wall; electrics were available, and he urged that benefit could be derived from their use, in combination with hydraulics.

For example, the author had mentioned the conversion of the high rotational speed of the motor (24,000 r.p.m.) into something which one could handle, some reasonably slow linear movement, by a hydraulic pump and jack set, preferably with a self-contained reservoir. That was a very attractive solution, if it could be developed satisfactorily. It could overcome the snag of emergency operation, which was the greatest difficulty in connection with the application of electrics to undercarriages; it would enable one to use compressed air or cartridge emergency gear, and it was in that connection that hydraulics could score particularly over the electrical design.

With regard to standardisation, he commented that Mr. Woodford had fallen into a trap into which all electrical firms in this country, or nearly all of them, had fallen; the tendency was to tell the aircraft designer that it was of no use asking for something special, and that he must select his requirements from their range of standard items. But surely they could not expect an aircraft designer to alter his aircraft geometry in order to suit them. On the contrary, they must design the devices to suit the job and must provide 100 per cent. flexibility; they must be able to produce anything reasonable that they were asked to produce.

The high efficiency electrical actuator mentioned by the author appeared to be one of the most attractive methods of applying electric motors to the operation of undercarriage or flap.

As regards up and down locks, the high-efficiency screw threads must be reversible in order to maintain efficiency; if irreversible, they were less than 50 per cent. efficient. One could lock up on the clutch; but how was release effected in an emergency? One could lock down presumably on the clutch; but that might not be satisfactory, and something more efficient might be necessary. Suggestions had been made to use a mechanical device equivalent to the internal lock on a hydraulic jack, and Mr. Conway asked for the author's considered opinion on the matter.

The great snag in connection with the all-electric aircraft was the operation of the brakes. Electrically-operated brakes had been contemplated in the United States, but the usual solution was to use hydraulics for the brakes. If hydraulics had to be used for brakes, a small motor could be used to drive small pumps.

Finally, Mr. Conway referred to the great difficulty of arriving at a satisfactory terminal, which, of course, had to be used on every electrical device. The existing M.A.P. standard terminal and the other types were not entirely satisfactory, and he had not found anyone who knew what was a satisfactory terminal. Therefore, he asked for Mr. Woodford's opinion on the matter.

Mr. B. L. WOODALL (Rotax Ltd.) said the author had put up a very good case for the adoption of A/C systems on large military and civil aircraft; and he fully supported the author's view that the voltage of the system should be 208 and the frequency 400 c/s.

In that connection he recalled a paper read before the Society in March, 1939, by R. H. Chaplin and F. Nixon, on "Ancillary Power Services on Aircraft," and said that during the discussion a number of speakers had recommended the adoption of such a system

with a voltage of 110. He asked why, six years later, we still had no installations of that type (with a frequency of 400 c/s) on either military or civil types of aircraft. It was true that the war period had to a certain extent retarded development; but it seemed that aircraft designers tended to avoid the distinction of being the first to try out a radically new system.

Dealing with the method of driving alternators, Mr. Woodall could not share the author's view that a variable voltage, variable frequency supply from main engine driven alternators would give the best arrangement for a large civil transport aircraft, where at least a 2:1 speed range of main motors was likely to be encountered, and possibly 3:1 if there were large power requirements at tick-over speeds.

Automatic induction regulators for the required constant voltage supplies would probably be heavy. Manual types would not find favour, since it was understood that the cruising speed of the craft would be falling over the period of the flight, and any fluctuations in the voltage of lamps would not, he imagined, be tolerated.

The development of constant speed drives was proceeding, and it was perhaps too early to predict whether, from the weight and reliability points of view, they would find favour. Turbines, of which one might have a choice of several types, would provide a good answer to the drive problem.

It was not felt that the petrol-engined auxiliary generating plant had had a fair deal, and in the case of the only A/C equipped aircraft now flying, *i.e.*, the Short "Shetland," a somewhat heavy a.g.p. had emerged from an excellent light-weight engine (the P.6 design of Rotol). As the author had rightly pointed out, such units could be housed in close proximity to the main engines, which would eliminate the somewhat heavy soundproof cover now associated with the a.g.p. mentioned. Furthermore, latest type alternators running at 8,000 r.p.m. were less than half the weight of the alternators installed on the "Shetland."

Until constant-speed drives or new forms of constant-speed prime-movers, such as turbines, were fully developed, there appeared still to be a field for A/C plant with petrol engines and, of course, the larger the electrical load on the craft, the more nearly would the power/weight ratio of the small engine approach that of the main engines. It was hoped that the small engine people would extend their development and would perhaps save weight by supercharging for altitude. A point which was often overlooked when comparing weights of main engine driven and auxiliary engine driven equipment concerned the adding of the proportional weight of the main engines to the alternator weight. With large installation involving 50 or 100 kW. alternators, the power taken from the engines is 75 or 100 h.p. respectively.

Mr. Wm. Armstrong (Institute of Aeronautical Sciences, New York): The author had put forward a very well developed case for high frequency services.

Discussing the part of the paper dealing with the major services, involving the transfer of heavy loads by either electrical or hydraulic means, he agreed with the author that there had been a great deal of development of electrical actuators, both of the linear and the rotary types, in the United States, and that a great deal of progress had been made; but he pointed out that there had been very little experience of such equipment in service. Some of the actuators were coming into service, and although he had no results of their use, he felt that to some extent one was optimistic in comparing present-day hydraulics with the anticipated future performance of electrical actuators. It was well to wait until they could see what the electrical actuators would do. There seemed to be a feeling in some quarters in this country that the American aircraft industry was swinging completely from hydraulics to electrical actuation; but, although there had been

certain changes, he would not say that that trend was yet very marked. The Douglas Company, the biggest and most active manufacturers of civil and commercial types in the States, had used hydraulics from the beginning. The B.29, built by the Boeing Company, was originally all-electric, but for the bomb-doors electrical operation was superseded by pneumatic operation because tactical considerations made it necessary to open the bomb doors in a much shorter time than was possible electrically.

As a further example, the Grumman Company, which manufactured probably the most highly developed American Naval type, used hydraulic operation. The Lockheed Company had changed from electrical to hydraulic actuation; and the Chance-Vought Company had introduced hydraulic actuation on the "Corsair."

Thus, although a great deal of consideration had been given to the electrical actuation of heavy services, there was not by any means the landslide that some people in England seemed to imagine. His own feeling was that electrical actuators had merit in certain cases, but they seemed fundamentally very complicated, and he felt sure they would be heavier, and certainly they would be more expensive, than the corresponding hydraulic actuators for heavy loads. Commenting on the author's example of energy transformation, he said the latest American hydraulic motors weighed considerably less than 1 lb. per h.p.; so that, in the case of the pump-motor combination, one could obtain 1 h.p. for a weight of considerably less than 2 lb. He questioned whether electrical transmission and conversion could compare with that in respect of weight.

On the question of reliability, he said there had been very little service experience with electrical actuators. Noting that in Section 3 (f) of the paper the author had discussed fuses and other safety devices in the electrical system, he said that the hydraulic system had recently been made considerably more reliable in the United States by the introduction of a valve which automatically closed off the system if trouble developed in any part of it; the trouble could then be eradicated or that particular part of the system could be neutralised, and the rest of the system could continue without interruption.

Supporting Mr. Woodford's reference to the trend towards the use of "power panels" in the States, where a generator fed various compact units of the electrical services, Mr. Armstrong said that those services involved an electric motor driving a pump, with the necessary hydraulic control gear. The arrangement visualised for large aeroplanes was to locate the panels at various strategic points in the machines and to use them for the services at those points. The next stage would be to use one power panel for two services, *e.g.*, the combination of nose wheel retraction and wheel brakes was visualised, using a very simple hydraulic change-over from one to the other. One could visualise various combinations of services which were never used at the same time. By such combinations one could logically improve the load factor on the power panel, depending on the number of services that could be put on to one panel.

In conclusion, he said the author had rendered a great service in focussing the attention of the aircraft industry on the electrical developments that were taking place; everyone, whether connected with an electrical or an hydraulic firm, was interested in the production of the best and most efficient aeroplane.

Mr. W. H. CAMPBELL (Metropolitan-Vickers): He wished to emphasise the point made by the author that the electrical industry was a potent force at the service of the aircraft designer, as there was still a tendency for aircraft designers to regard electrics as something of a novelty and of somewhat doubtful performance. This was natural in view of the fact that many applications of electricity to aircraft were new, but it must be remembered that the application of electricity to services similar to those required in

aircraft engineering were not new; all that was required to ensure the complete success of electrical operation in aircraft was the diversion of more and more effort on the part of the electrical industry to the problems involved.

One must always expect proposals with regard to electrical actuation to be criticised by hydraulics engineers; but he pinned his faith to the fact that electrics had superseded other forms of power in ordinary industrial engineering, not by any accident of circumstance, but due to the various inherent advantages of electricity, such as its ease of control, the ease of its conversion to heat, light, and power at the point of application, its general cleanliness and the ease with which it could be transmitted and distributed. An additional inherent advantage of electric power had been appreciated since its application to aircraft, namely that the electrical system was less vulnerable in combat than were hydraulic and air pipelines; a very important factor in military aeroplanes.

Mr. Campbell then discussed some experimental electrical equipments which had been designed and manufactured, and others that were being designed, which compared very favourably on the weight/performance basis with hydraulics. There was in course of design and development an electrically-operated undercarriage for a very large aircraft which, on calculation, was of a weight comparable with that of the latest high-pressure hydraulic systems. The design incorporated a system of pneumatic operation for emergency use.

Referring to ball bearing screw actuators, the author mentioned an efficiency of 50%, but this obviously included a rather excessive allowance for the gearing which was always required in addition to the screw.

An earlier undercarriage actuator which had been developed and tested employed a chain type winch of a special kind, in that the chain was closely guarded by means of tubes so that it could be operated by one sprocket in both directions under power and the undercarriage could be locked down by means of two collapsible links which fell into a receptacle in the guide tube assembly. It therefore worked as though on the endless chain principle, the radius rods being pulled up on one side of the endless loop. There were four such winches (two per wheel) driven from a single gear box and motor unit mounted in the centre of the fuselage. The equipment had been exhaustively flight-tested at Boscombe Down. The retraction time at 1.5 V/S was $8\frac{1}{2}$ seconds, and the lowering time was $5\frac{1}{2}$ seconds. The undercarriage had been lowered in a shallow dive against more than 2 V/S. During all the flight tests no maintenance work whatsoever had been carried out on the equipment. The overall mechanical efficiency of the winches and gear box was of the order of 75% and the experience on this aircraft showed that a saving in weight of more than 20% as compared with the existing low-pressure hydraulic system could be achieved provided the flaps as well as the undercarriage were converted to electric drive.

He mentioned this installation not in order to forecast that that particular design had a wide general application, but in order to show that reliable electrical equipment competitive in performance could be designed.

Whilst he agreed with the author that electrical engineers did not expect the aircraft designer to design aircraft to fit round the electrical actuator, they did consider it rather restrictive to be expected simply to fit a jack between exactly the same centres as for an existing hydraulic jack.

Whilst developments in the larger actuators would tend to employ the ball bearing screw jack in order to minimise electrical input, for the smaller range of linear actuators high mechanical efficiency was not so important and it would continue to be more economic to use Acme screw jacks. With regard to these smaller actuators, designs were being dealt with in connection with which consideration was being given not only to the co-axial design with the epicyclic gear drive, but also the parallel bi-axial construction with

spur gearing. He believed that actuators with the smallest possible distance between centres of the points of application were likely to be more easily applied and this would favour the bi-axial design.

With regard to the use of the A/C system, he said the author was looking very much to the future; it must be admitted that at the present time much of the very necessary 400-cycle equipment was still only in the early or intermediate stage of development, at any rate in this country. Further, he was not certain whether a clear case could be made to establish, say, 40,000 lb. all-up weight as the dividing line at which the A/C system became the unanswerable one for the electric supply; the weight savings were not so spectacular when dealing with the more moderate power demands associated with medium to small aircraft.

The author did not favour parallel operation of M.E.D. generators even where these were D/C machines, but a part from the advantages normally associated with this practice, there was an advantage in parallel operation which might be regarded as especially important on civil aircraft. This was the better voltage regulation under normal conditions which would obtain during heavy short-time loads such as the undercarriage and flap operations. If, for example, the undercarriage were normally supplied from only one generator, this would have a very marked effect upon its capacity and therefore weight for a given performance under short-time rated conditions.

In all electrical work on aircraft considerable standardisation and regulation was necessary, and the efforts of the S.B.A.C. and the I.E.E. in that connection were noteworthy. The I.E.E. was drawing up regulations governing the use of electrical equipment in aircraft, and he was sure that that document, when published, would be of very great service to the aircraft industry.

Mr. Ivor Bowen (Fellow): He deprecated the tendency of the discussion to confine itself to the competition between electrics and hydraulics, and pointed out that the author had not really tried to embark exclusively on a discussion of their relative merits. He suggested that the meeting would do more justice to an excellent paper if, recognising that every aircraft would have to use electric power, if only for heating and lighting, and that the problem of generation and distribution remained, more consideration were given to how best to deal with that problem. New applications would be found as the use of electricity developed, and the paper indicated how much was being done by the electrical engineer, who had worked quietly for a long time in the background, so quietly that probably there were very few people who knew of the "Shetland," which was planned some years ago and which was using A/C at voltages higher than had been used in aircraft in the past.

The Ministry of Aircraft Production held no bias for either hydraulics or electrics, recognising that there was a place for both; but there might well be a greater place in the future for a combination of both, using electric transmission lines to control hydraulically-operated units which would effect the actuation.

It was pleasing to note the author's tribute to Mr. S. Neville for his pioneer work, which was published in his last report.

In Section 7 of the paper the author had quoted from American sources a list of objectives in order of priority, according to the Americans. Mr. Bowen suggested that, whilst reliability was of very high priority, the Ministry would place ease of maintenance much higher than the Americans had placed it. It was felt that A/C had the advantage of simplicity which would reduce maintenance almost to zero, and that it should be a prime objective of the electrical engineer, in developing the systems, to ensure that maintenance in the field was so reduced.

Another objective of importance should be to design something that would withstand very severe overloading without breakdown, even though replacement might be necessary

after the emergency overload had been imposed on a component. For instance, the author had mentioned the desirability of insulating electric cables with fireproof materials such as glass. One had seen glass in generators and motors, but no development seemed to be in hand for glass insulation of distribution cables. There was another possible great advantage in electrics with good heat resisting insulation, namely, that they could be seriously overloaded and yet carry on to the termination of a flight, after which replacement could be effected at a convenient time.

In his experience during the last few years in fostering electrical developments in the industry and in the Ministry he had seen growing up a very close accord between the electrical engineer and the aircraft designer. Nevertheless, he felt that they must go a long way further yet. The aircraft designer had to recognise the increasingly complex problems that were coming his way and must raise the standing of electrical personnel working within the aircraft firms. At the same time, he should give more confidence to the electrical firms and use their experience to a greater extent.

The Ministry's work in that field was to encourage the electrical industry to gain experience where the aircraft industry itself was not demanding sufficient. It was doing its best to make available ranges of apparatus —alternators, contactors, A/C motors, frequency compensators, and so on—which, although they might not find complete favour with the aircraft industry, would to some extent provide a nucleus of components which could be adopted where suitable. It was not contended that those ranges were necessarily final.

There were very serious problems to be faced by the electrical engineers before high voltages A/C could come into wide use in aircraft with complete confidence. There was scope for the electrical engineers to tackle specific problems such as the development of new forms of constant speed drives; there was much to be done in the evolution of such gears. Other problems included the development of exhaust turbine drives and possibly gas turbine auxiliary sets. If those could be developed they could take advantage again of the possibility of constant voltage and constant frequency particularly, and also make more use of higher speeds and, therefore, the great savings in weight of alternators. Circuit breakers also would be needed for various applications, and new methods of alternator excitation to be applied to engine driven alternators running at variable engine speeds with the object of obtaining therefrom constant frequency and voltage.

The speaker felt convinced that a large field of new endeavour had opened up before the electrical engineer, and Mr. Woodford's paper would go far to demonstrate how fascinating will be that field to the young A/C electrical engineer who is prepared to devote himself to work therein.

Group-Captain WILLIAMSON (David Brown Ltd.: Fellow): Speaking as one who was an electrical engineer, and as one who had been for 30 years a pilot and for a similar period a maintenance man, he agreed very heartily with the view that on neither side of the Atlantic would there be any landslide in favour of electricity *in toto* in aircraft. He believed, however, that ten years hence a good proportion of the services in aircraft might be electrical, though there would still be at that time a few hydraulic services. In 30 years of flying he had never experienced a hydraulic failure; but neither had he experienced an electrical failure. Troubles had occurred always with carburettors or magnetos or petrol, or something of that sort. So that, in the future, either with electricity alone, or hydraulic actuation, or a combination of the two—the last being by far the most likely—they would achieve a good position in respect of maintenance and reliability from the pilot's point of view.

One could have wished that Sir Frederick Handley-Page were present at the meeting, for he, too, began life as an electrical

engineer; the Royal Air Force in particular, and aviation in general, owed him far more than they knew on the electrical side. As the Ministry and the M.A.P. were aware, he was the man who had suggested the electrical actuation of bomb-release gear. Again, nearly 15 years ago Sir Frederick had suggested something else; he had suggested to Lord Dowding, then Air Member for Supply and Research, that plug-and-socket wiring should be employed on military aircraft; and the production of military aircraft would have been somewhat improved if they had taken his advice then.

By reason of their experience of large aeroplanes built before the war, civil aviation would not depend on plug-and-socket wiring; and from the wireman's point of view, that was all to the good. He had been told by B.O.A.C. engineers that the Empire flying boats were wired throughout with only the minimum of connectors, and that when the boats were dismantled after six years of hectic life the wires were good enough to be used again.

Whilst approving heartily the author's suggestion for increased size of generators, he was disappointed that nothing had been said with regard to following marine practice and having independent turbo-alternators housed in a wing or anywhere else, so that we need not overhang a generator on the end of a shaft. He would like to abandon the main engine-driven generator, if that were possible.

A matter to which he took exception was the author's forecast of the possibility that failure of the oil supply in a Merlin might switch the engine off before it failed. If that occurred on take-off, it might make all the difference between saving the passengers and the aircraft and saving just the engine. The pilot might very well do with another 60 seconds' running of the engine, even if that meant ruining the engine. The use of a warning light to indicate that the oil supply had failed would be better than to switch off the engine and thus leave him with one dead engine on his hands.

They had good experience of the electrical operation of undercarriages, at any rate with D/C, on at least two types. Group-Captain Williamson thought highly of the suggestion to use a very high speed motor to drive a pump to deliver liquid from a tank locally, using hydraulic-cum-electric actuation, but with the advantage that considerable lengths and weight of piping would be saved.

Mr. F. BUTCHER (Rotax): As an electrical engineer, he gave general support to the author.

Dealing with specific points in the paper, however, he disagreed with the suggestion in Section 3 (c) with regard to the earthing or grounding of the alternator neutrals solidly to the airframe, for that introduced the factor that earth protection gear must be of comparatively high current rating. Further, the occurrence of an earth fault necessitated its immediate clearance by the protective gear in order to remove the danger.

Another system, which had given very good results in other industries, was to earth the neutral via a high impedance relay. The occurrence of an earth fault was then immediately indicated, but it could be allowed to continue without danger until it was convenient to make other arrangements. In exceptional conditions the period could be extended until the end of the flight.

Duplication of circuits went a long way towards covering the broken line condition.

With regard to Section 3 (d), he suggested that more emphasis could be placed on the advantages in some applications of using 24,000 r.p.m. motors. He did not agree that 2-pole motor construction gave less favourable conditions than 4- or 6-pole construction. Tens of thousands of the former type were in use in portable equipment, giving very satisfactory service. Suitable short-chording of the windings was used in order to reduce the hangout length; and the problem of the operation of bearings at speeds of 24,000 r.p.m. was well on the way to solution.

Wing-Commander M. J. SMITH: In view of the wide scope of this paper, it was only natural that many aspects of the subject be left out. He felt, however, that since the idea of the paper was to crystalise the views of aircraft designers, that any point which might tend to disturb this crystalisation should be presented now and not come up from another source later on as something totally new, and so upset the designers. He referred to the fact that no mention was made of the 120 volt D/C system.

He wished it to be clearly understood that he was not at all in favour of this system, as he was a confirmed advocate of 3-phase alternating current for aircraft use. He felt, however, that the pros and cons of the 120 volts D/C system could have been included.

In the past, people had dismissed the 120v. D/C system with the airy assumptions that commutator trouble, arcing, ionisation and the difficulties of circuit interruption at high altitudes would make 120v. D/C impractical. Certainly these points were borne out when tests were originally carried out, but then the tests were carried out on equipment which closely followed that 28.5v. D/C practice. Recent tests in America on equipment specifically designed for 120v. aircraft application, showed that little difficulties were likely to be encountered in this direction. A good case could also be made for 120v. D/C on a weight basis, the overall weights of an electrical system for an aircraft of all-up weight of 75,000 lb. indicating that the 208v. 3-phase 400 cycle A/C system showed no advantage. The whole point, however, was that ease or otherwise of maintenance played a very large part in deciding what the electrical system of the future should be, and no one who had seen the reduction in maintenance which could be obtained due to the absence of commutators, brushes, etc., wished to retain them in the system. Moreover, changes of voltages for lighting and other uses present considerable weight disadvantages when the D/C system was considered.

The disadvantages of the system were fairly clear, but it was felt that this point should have been brought out in the paper to avoid misunderstandings at a later date.

He quite agreed with the author that they did not want to see the term "boost" used in connection with power assisted controls, but he rather doubted whether the term "electric servo" was correct. A servo mechanism was one in which the output bore no relation to the input power, whereas, particularly when discussing flight controls, the output power should bear a definite relation to the input power, and with mechanisation of this nature he felt that the word "torque amplifier" was more correct than "servo." It was probable, however, that the word "servo" would come to stay since it was in fairly general use, and was much easier to talk about than "torque amplifier."

The only main point on which he disagreed with the author on his views that non-parallel operation was preferable to parallel operation with A/C systems. One could not help but feel, listening to this paper and also from views one heard in other quarters, that people were rather over-awed by the difficulties of obtaining parallel operation, chiefly due to the difficulties of obtaining a constant speed drive. It would appear that having seen some of the apparent difficulties, people looked around for what could be said against parallel operation before stating their case, but he questioned many of the points stated in this paper. For example, it was stated that with non-parallel operation the disturbing effects of sudden over-loads or faults was avoided. He could think of no more sudden or disturbing over-load occurring on an alternator than when equipment was suddenly connected to it by means of the automatic change-over switches when the alternator or engine which was previously feeding the equipment failed. It was also stated that it would reduce congestion at the wing roots, increase cable runs, voltage drop, etc. This he very much questioned. If it was necessary to have a complete stand-by for essential services, additional cables must be run to

avoid what the author tried to avoid, a central switching station.

In military aircraft the emergency condition when one engine had failed was the very time when the electrical system must work at its maximum efficiency, as probably maximum power would then be required, particularly for the Armament equipment. The extra cable runs involved in getting this with automatic change-over switch-gear would increase the voltage drop and so tend to reduce the power at a time when it was most wanted, unless a weight penalty is incurred. One of the advantages of a parallel operation was that owing to the large power capacity that was available any earth faults which do occur (assuming that the generator neutral points were earthed) burn clear very quickly, due to the large flow of current which would flow.

The author stated that a constant speed drive of some form would probably be an essential requirement for certain loads, and Mr. Ivor Bowen earlier in the discussion stated that this load would represent about 6 kW.

In endeavouring to obtain a constant speed drive of loads of this order, one might just as well be logical and start with the constant speed drive on the main engine, and not introduce it later on.

He could not help feeling that the author had a sly regard for parallel operation, as he stated that if and when turbo-alternators were used, parallel operation might claim consideration. It would appear that the deciding factor was, therefore, if a constant speed drive could be obtained, and his personal opinion was that if A/C systems were to be the reliable source of all power for auxiliary systems in heavy military aircraft, then parallel operation was essential, and that more time and money should be spent on the development of a constant speed drive than appeared to be the case at the moment.

There was one further point on which he would like to question the author, whether the weights of the British alternators were given less exciter. It was also stated that an alkaline battery might be included to provide initial excitation of the A.G.P. or to any main alternators if required.

Did one infer from these statements that Mr. Woodford was not in favour of using D/C excitations for his alternators, but proposed to use residual magnetism to obtain initial build-up and then obtain the D/C excitation from rectifiers on the A/C side? He felt that if one was to maintain the advantages of keeping the system's voltage as normal as possible, then D/C excitors should be provided as the system voltage can be more readily maintained by this means than by any form of rectifier excitation of which he had knowledge.

Mr. R. H. CHAPLIN (Hawker Aircraft: Fellow): He was encouraged to take part in the discussion particularly in view of the reference made to the paper on ancillary power services which Mr. Nixon and himself had presented to the Society in 1939. Mr. Woodall, who had recalled that paper, was almost indignant that a certain electrical system that had been mentioned at that time had not been adopted on aircraft. The answer was obvious: it was not sufficiently attractive.

Endorsing the tribute which the President had paid to the author when introducing him, Mr. Chaplin added that at the same time it served as a warning. The author was so enthusiastic as to give the impression that nothing was possible other than electrical operation on an aeroplane. But he pre-supposed that already reliable electrical equipment was available, whereas in fact that was not so. Various aircraft designers, including those of his own Company, had used electrical devices from time to time, and those devices had given quite a lot of trouble. Two vested intests were represented by various speakers in the discussion, *i.e.*, the electrical and the hydraulic. The fact was that neither was perfect. Mr. Dowty and Mr. Woodford respectively had stated that neither system

had given any trouble in service. The fact was, however, that both those systems had given a considerable amount of trouble!

A point which had been made by Mr. Conway, and which the electrical interests must bear in mind, was the importance of flexibility in the early development period. There was no doubt that at present there was much more flexibility in hydraulic equipment. The aircraft designer could have it designed exactly to his requirements. Another speaker seemed to consider it unfair that the aircraft designer should desire that state of affairs; if one could get that service from the hydraulic engineers, that was another reason why one would use hydraulics.

Mr. Chaplin sought amplification of a statement in Section 4 (c) of the paper that "... while all the complexity of the electrical method can be thus concentrated in the actuator, that of the hydraulic method is distributed over a larger part of the aircraft. ..." Surely, he said, the complication in the hydraulic method was largely the jack, and the jack was comparable with the actuator; therefore, he could not appreciate the point of the discrimination between the two.

On the question of development, he pointed out that in the hydraulic apparatus the jack was comparatively simple; one could arrive at a design and could pre-determine the results that would be obtained. On the other hand, there were so many things which could go wrong, and which in fact did go wrong, in an electrical actuator that it required quite a lot of development work. For example, there were brakes which refused to go on or to come off, and there had been trouble with oil used for lubrication purposes in the actuators getting on to the electrical mechanism. Such troubles had occurred constantly, whereas they did not occur with the hydraulic jack.

Mr. G. W. MULLETT (Short Brothers Ltd.) *Contributed*: Whilst it was true that aeronautical designers and engineers were essentially mechanical engineers, it was only fair to say that most industrial electrical engineers have had very little experience of aircraft. Of recent years, however, the number of aircraft electrical engineers available in the aircraft and electrical industries had been steadily growing, but this number was still yet very small and he thought everything possible should be done to train and recruit new members.

He was in agreement with the general electrification of aircraft services, particularly in the case of boat-seaplanes. Mr. Woodford's statement that the existing 24 volt D/C system reached its limit in aircraft of 50,000-70,000 lb. all-up weight was true. In aircraft of this size, cable weight became a problem, the particular offenders being the heavy section cables required for engine starting and propellor pump motors. The greater part of the cable weight of an aircraft was contributed by these heavy section cables. Reduction in these sections would produce very substantial savings in weight. Cables available for aircraft are widely spaced in ratings and it was sometimes not possible to select a cable just suitable for the circuit; frequently the cables are oversize due to this limitation of choice. Again, battery weights were becoming important, 200-300 lb. for these large aircraft. Electricity will always be present in aircraft, mainly for radio, instruments and lighting and it seemed a logical step to extend the supply to such domestic services as heating and cooking and to the various operational services such as main plane flaps and oil cooler shutters.

He agreed that a comprehensive range of power actuators was needed to cover the complete range, say from a fuel cock to an undercarriage. It will be extremely difficult, however, to produce from the start standard actuators which will satisfy the numerous aircraft designers in the country. It seemed to him to be a little early to attempt standardisation, but, as their popularity increased and electrical firms turned out actuators to meet individual needs, it would be found that standardisation would be automatically ac-

complished because the actuators made would uniformly fall into well defined groups suitable for standardisation.

Mr. Woodford seemed strongly in favour of main-engine-driven alternators, but he considered that the use of A.G.P.s was very attractive. His main objection to A.G.P.s appeared to be on the score of weight and possibly reliability. Several years ago the writer attempted what was at the time, an accurate weight estimate of these two conditions, *viz.*, main-engine-driven and A.G.P. alternators, and he found that there was very little in it. It was to be regretted that the "Shetland" aircraft was still on the restricted list and information on this aircraft was not yet available for publication. He was able to say, however, that the A.G.P.s in the "Shetland" had functioned very satisfactorily with an absence of noise, vibration and smell and any other qualities about which doubt was expressed in the early days. It was agreed, however, that the use of A.G.P.s at high altitudes—the "Shetland A.G.P.s were rated at 12,000 ft. only—would produce supercharger problems, but there was no reason why the A.G.P.s should not be positioned in the pressurised cabin or a pressurised engine room and the main supercharger for the cabins be used for the A.G.P. engines. The point whether aircraft, particularly passenger carrying aircraft, really require to fly above 12,000 ft. was still an open one.

With the roominess of the boat-seaplane the question of the space occupied by the A.G.P.s did not really arise. All the problems associated with the use of main-engine-driven alternators such as voltage and frequency variations, leading to constant speed drives or special provision of constant voltage/constant frequency supplies for equipment that must have this constancy, disappeared. With A.G.P.s full electrical power was available on the ground and the aircraft was independent of ground supplies, a favourable point if the aircraft landed away from a base. Power was available for preheating the cabins before the passengers boarded the aircraft, for refuelling, for operating loading winches, for cooking, for the radio, etc., etc. It was also available for functionally testing all the services during inspection periods. Although Mr. Woodford made a point of taking his power from the nearest alternator, this seemed to be an open question since all the power was required in the hull or fuselage and ultimately had to be taken there.

The proposed system for civil aircraft, *i.e.*, an equipment line voltage of 200, 3 phases, 400 cycles and the neutral point of the alternators joined to the airframe had been well debated and must be a suitable choice, but two points should receive further attention. In the first place, most of the larger power requirements would be balanced loads on the 3 phases and it seemed as if the neutral wire current would be small. Weight saving by using the airframe as the neutral wire would thus be small and he personally queried its use. Surely it would be better to have a fully insulated system which brought with it increased safety, and, nearly as important, the greater ease with which the system can be insulation tested. In the second point, he hoped that the speed of motors would not be over done. There seemed to be little use in having motors running at 12,000 r.p.m. if they were required to drive pumps at 1,500 r.p.m. since the attendant weight of the reduction gearbox then became a problem. Another difficulty associated with high speed-low torque motors was found with oil seals which could produce frictional torques on the motor shaft forming a substantial part of the motor working torque.

In conclusion, the main engines of the aircraft were frequently referred to as the heart of the aeroplane, and he agreed with Mr. Woodford that the electrical system was very rightly the nerves and arteries of the aeroplane. Very valuable work had been done recently in emphasising the importance of these nerves and arteries and he thought that most aircraft firms had now placed their electrical sections on a firm footing so that

their installation received its proper position in the design and manufacture of the aircraft. The work of the S.B.A.C. in this connection was noteworthy and it was to be hoped that now that the standard wiring system was an established fact the work would go on to include other items of the installation. Mr. Woodford stated that the electrical industry were willing to co-operate with the aircraft industry on the general electrical problem. They could now hope that, in due course, the old methods of changing cast iron to light alloy in commercial apparatus to adapt it for aircraft use would cease and equipment specially designed for aircraft would become available. It was also to be hoped that the conservative ratings usual with commercial equipment would be "hotted-up" and the maximum power for minimum weight consistent with reliability would be offered.

Mr. I. O. HOCKMEYER (Associate Fellow) *Contributed*: One speaker remarked that the increasing use of electric power in aircraft was inevitable but it might be thought that the electrical engineer himself was doing little to further this end, since he has failed lamentably to describe the possibilities of "electrics" before the Society and before the I.E.E. The electrical engineer had in fact been thinking hard over the problems of intensive electrification for at least ten years, as witness the discussion at Chaplin and Nixon's paper, the scheme adopted for the Shetland, and, more recently, the work of Mr. Neville. It was to be hoped that, in future, technical literature, in the English language, would not be exclusive to American journals.

He had been an ardent supporter of the A/C system since 1937, for it had definite advantages, such as its lighter weight, the ease of transformation, reliability of squirrel cage motors and the absence of running contacts, leading to lessening of maintenance and elimination of the radio interference problem. The early view that the drive had to be of constant speed—to give constant frequency—led to the conclusion that auxiliary petrol engines were essential, because constant (output) speed gearboxes or other forms of auxiliary prime mover were not yet in sight of being practicable. This view had been modified by Mr. Neville's realisation that variable frequency (with proportionate variable voltage) was not inimicable to the majority of power services; a constant speed device would be provided to supply the remaining services, for which a constant frequency was essential. There was a very reasonable possibility that a constant speed device, for a limited amount of power, was practicable.

One criticism levelled at the Shetland was the fact that three separate electrical distribution systems co-exist, *viz.*, 110 volts, 3-phase, 29 volts, single phase, and 24 volts D/C. There was a danger of the proposed scheme being open to a similar criticism, where the supplies would include 200 volts, 400 cycles, 3-phase, variable, 115 volts, 400 cycles, 3-phase, constant, special power supply (at perhaps 1,600 cycles). Services requiring L.T. A/C (29 volts) and D/C (24 volts) would be supplied by local conversion from the main supplies: that is they would not add the fourth and fifth distribution systems. It seemed to him that the ideal would be the use of an auxiliary prime mover of the gas turbine type, running at high constant governed speed, and that the development of such an engine, suitable for high altitude conditions, was now an urgent necessity. He felt that this would offer the aircraft industry an ideal auxiliary power supply system and would remove opposition from those electrical engineers who were sceptical of the present proposals, either because they distrusted the variable frequency scheme, insisted that paralleling is essential or doubted the successful completion of the design of a constant speed gear box.

Mr. F. P. WILLS (R.A.E.: Associate Fellow) *Contributed*: The widespread enthusiasm for the proposed adoption of three phase A/C supplies on aircraft ignored the advantages which exist in the D/C systems now in use.

It was claimed that D/C could not be employed because of at least two grave defects:

(1) Brush and commutator wear at high altitudes;

(2) The impossibility of switching and suppressing contact arcs at altitude.

It could be claimed at once that for a 30 volt D/C supply, brush wear on generators, inverters and motors at high altitudes up to 40,000 feet was no longer a serious problem.

The main cause of the brush wear which was experienced when the 6 and 9 kW. 30 volt generators first came into general use was the high average brush current density.

In order to make the brushes and commutators small enough to be accommodated in the space available very high brush current densities had to be used. They were actually 221 amperes per square inch on the 6 kW. 200 ampere, and 200 amperes per square inch for the 300 ampere American generators.

These brush current densities were about three times the values normally used on brushes of all types in electrical machines. However, U.S.A. A.F. Specification for these generators made the size and weight so small that such high current densities were absolutely essential.

As soon as the brush wear became manifest in U.S.A. the problem was tackled on a large scale and the various factors were now well known.

Special impregnation of the brushes ensured that their durability was improved to some hundreds of hours.

See High Altitude Brush Problem, by Ramadoff and Glass, A.I.E.E. Transactions, p. 825, 1944.

If the D/C supply voltage was increased to 120 or 210 volts then the brush densities would be cut down to 70 amperes per square inch with great saving in weight of the commutator and for less brush wear than was now attained with the special high altitude treatments.

It should also be borne in mind that alternators employ both slip rings and excitors. So that brushes still remain an essential part of A/C generating systems.

D/C Current Rupture.

It was always claimed that D/C currents could not be broken at altitude. Actually this is quite untrue. No work had been done in this country on this problem. However, in America, experiments had been made which show that the higher voltages 120 to 210 volts were much easier to rupture at altitude than the lower voltage of 30, and that they can be dealt with by careful design.

See Peak Voltage with D/C Arc Interruption for Aircraft by Phillips and Mitchel, A.I.E.E. Transactions, p. 944, 1944.

D/C Arc Interruption for Aircraft, by Quill and Rader. A.I.E.E. Transactions, p. 883, 1944.

High Voltage D/C Aircraft Electric Systems, by Berry and Dallas. A.I.E.E. Transactions, p. 843.

Motors.

D/C motors had the very great advantages of extreme flexibility. They could be given series, shunt, or compound characteristics, which could be made to match any required conditions of torque and duty cycle. Three phase induction motors were much more restricted in the shape of the speed torque characteristic.

System Operation.

On transport planes the engine speed started high and was tapered off so that the speed range would be 3/1, so that frequency and voltage would vary in this ratio, whereas with D/C the voltage could be kept constant over the speed range. Thus A/C supplies for radio with D/C motor driven alternators could maintain the 1,600 cycle supply absolutely constant.

A.G.P.

The starting of auxiliary generating plants at altitude would be difficult. In the D/C case there was a generator on each engine all paralleled, and the A.G.P. would only be

used on the ground or when coming in to land. It would not need to be operated at high altitudes and so need not be supercharged.

Lighting.

Fluorescent lighting could be used on both A/C and D/C supplies.

Distribution.

Mr. Woodford ignored the complexities of distribution in the A/C non-parallel operation supply. Upon failure of one or more alternators, automatic redistribution of the load had to be performed. This was only possible if an automatic central distribution panel was incorporated. This would necessitate 3 core cables running from each engine-driven alternator to the panel and then back again to the segregated loads. The distribution would also have to be automatically balanced to discriminate between each non-parallel circuit and its alternator and the load that it might be called upon to supply.

With a 120 or 210 volt D/C system all generators could be worked in parallel. No distribution panel of the cumbersome complexity mentioned above was necessary. If one generator failed it is simply cut off the main supply by a cut-out, while the wiring for 210 volts D/C on aircraft would use less copper, less insulation and fewer conductors than the 3 phase A/C system.

Rectifiers.

It had been said that high D/C voltages were more easily attained from 400 cycles A/C supply for radio purposes by light-weight static rectifiers than by rotating transformers. Actually it was found that rotary transformers were lighter and smaller than static rectifiers with their transformers, selenium rectifiers, condensers, smoothing chokes and possibly motor driven fan cooling for the rectifier.

On the whole, it could be safely assumed that the most desirable system of the future will be 120 or 210 volts D.C. with engine-driven generators and an A.G.P.

REPLY TO THE DISCUSSION

Mr. C. G. A. WOODFORD: He was very happy to find that most of the technical points raised seemed to have cancelled each other out; thus, he would not deal with them all individually.

His purpose was not to declare war on hydraulics. He had not merely been shot at, but squirted at! But, curiously enough, he had rather anticipated it.

Dealing with the specific question as to why all the complexity of the electrical system could be concentrated in the actuator, whereas that of the hydraulic method was distributed over a larger part of the aircraft, he illustrated by means of slides an electrical and a hydraulic scheme for undercarriage retraction on the outline of a well-known medium-size bomber used in very large numbers by the United Nations. The first showed an electrical layout, where each leg was powered by an actuator, the whole of the wiring system being laid out neatly. The second showed the layout of the existing hydraulic system, and indicated each of the lines. There were various circles which, he said, represented "the funny little bits and pieces on the hydraulic system, the shuttle valves and all the funny little things which never went wrong—or so we were told—and which required no maintenance at all."

The troubles that one experienced, even in electrical power operation, were mechanical rather than electrical. But one was up against that problem in any piece of machinery.

Another important question was that of availability. One or two speakers had said that the electrical equipments which he had asked them to consider were not yet available; but neither were the aircraft in which it was hoped to fit them. He believed the electrical industry would beat the aircraft industry to it, and that was why he asked for consideration of electrical systems. If they were not now considered the advantages of simplification in aircraft services for some time to come would be missed. In emphasising simplicity as the keynote, he asked that it should

be considered very strongly, because it was not being emphasised in America.

Expressing agreement with Mr. Conway's request for better terminals, he said he hoped it would not be long before the electrical industry could give him some.

The point made with regard to designing for electrics was reasonable. Electrical engineers were not asking the aircraft designer to change his ideas so far as the aircraft itself was concerned; they merely offered him means for carrying out his operations, and offered to help him to consider the best way to apply those means. After all, one did not first design a steam locomotive and then take out the engines and instal a motor; one designed it in the first place as an electric locomotive. Similarly, if they were to achieve in aircraft the simplicity of generating all the ancillary power electrically on an alternator, instead of using half-a-dozen auxiliaries or accessories, they then had means open to them of considering how best to apply the electrically transmitted power at the points at which it was required. Obviously, at some stage electricity must become mechanical power. Whether it was applied by high pressure oil from a pipe or through teeth around wheels was a matter to be decided from a study of design and application. He wished to emphasise to the user of electrics that the aim was to give him complete dependability through the simplification based on the A/C system.

It seemed that Wing-Commander Smith had answered his own questions with regard to the 120 volts D/C system. Mr. Woodford said he had avoided reference to it in the paper particularly because he wished to avoid multiplicity of systems. The change from low pressure to high pressure and from D/C to A/C were just twin brothers; and he was able to recommend the change from low pressure D/C to medium pressure A/C in one step because only in that way could they achieve all the advantages he had tried to put forward.

He had not wished to go into details in dealing with the comments raised on paralleling, because many of the comments had answered others. He was against the paralleling of generators, whether D/C or A/C, in aircraft, some of the reasons for which he had expressed. But in respect of paralleling turbo-alternators he was not suggesting that they should merely dodge the issue at the present time and come back to it when it was easier. He believed it would crop up again when they came to turbo-alternators, because they would have only two alternators per aircraft; they could then go to higher powers for these sets. The suggestion would be that in each wing there would be a turbo-alternator between the two engines, that as there would be only two turbo-alternators operating in the aeroplane normally, the question of paralleling raised a new issue, and it would be at the same time much easier. In fact, alternators of that size would have such strong synchronising torque that there would be no difficulty in keeping them in step when driven by turbine discs. If one wanted parallel working one should hurry up and get on to the turbo-alternator. But for the immediate future he suggested the large output alternator driven by the simplest possible means from each engine, with a similar auxiliary driven one carried for standby at take-off and landing.

Mr. Woodford gave the following written replies to the points raised in the discussion.

Mr. Dowty (Dowty Equipment Co.).

He was afraid that some of the comments made were rather too tendentious to be susceptible of reasoned reply and were not entirely consistent with the proposals made in Mr. Bound's lecture on March 22nd, which showed the future of hydraulics to be electro-hydraulics. Only thus was it permissible to eliminate the complexities of the hydraulic transmission system, and it would be clear that the electric transmission system was not troubled by low pressure and temperature, or by sharp bends in the runs.

While completely standardised jacks may not be attainable, a certain amount of com-

mon design in regard to the rotary portion was possible by group design over the power range, and by the adaptation of various output screws, individual requirements of stroke, thrust, and pick-up details could be met.

Regarding generator weights, these could be substantially reduced in proportion to output in the new A/C system through the much wider adoption of electric power. The cost of the new A/C high capacity generators would also be more attractive than for D/C machines hitherto.

Referring to the total weight of a hydraulic installation quoted at less than 300 lb. for a 75,000 lb. aircraft, it would appear that every other aircraft fitted with hydraulics had been unduly penalised. Or perhaps there was more to it than was apparent in this information.

Mr. H. G. Conway (Messier Aircraft Equipment).

It was noted that weights given for hydraulic installations are more representative than the case quoted by Mr. Dowty. He was in full agreement with Mr. Conway's comments except that he did not expect the aircraft designer to alter his geometry to suit a hypothetical standard jack. As indicated above, the designer and user will be able to take advantage of a measure of common design with individual adaptation. He had previously expressed the opinion that there might have been more use of hydraulic brakes in British aircraft.

Mr. Woodall (Rotax Limited).

In regard to the driving of alternators at constant or variable-with-engine speed it was necessary to bear in mind that the electric motor driven services were suitable for operation proportionately with engine speeds and therefore the power to be handled at constant speed was much less than with constant speed drives supplied to all the main alternators. Consequently to meet a speed range of 2 or even 3 to 1 for all the electric power generated would seem to be unnecessarily heavy as well as involving more maintenance than converting a small amount for instruments and radio and regulating the voltage for lighting supply. Certainly turbo-alternators should provide a solution for the future.

Mr. William Armstrong (I.Ae.Sc., N. York).

The expression of this contributor's views was widely appreciated. From them it seemed fairly clear, as the author had endeavoured to show, that the real issue on the full use of electrics could only reach finality on a basis of the new possibilities with the A/C system of eliminating commutators and thereby providing simple rugged motors, which could, where needed, be used with localised hydraulic or pneumatic applications as an alternative to mechanical gearing in actuators.

Group Captain Williamson.

He had shown justifiable concern for certain practical points in the electrical installation and shared the common feeling of need for simplicity in the aircraft wiring. The wish for independent turbo-alternator would be found duly emphasised in the text of the paper. He also noted his reference to the possible need to kill a dying engine after extracting a few seconds of precious operation to avoid crashing the aircraft.

Mr. I. Bowen (M.A.P.).

He was greatly indebted to him for his comments giving the correct perspective to the picture he had sought to present. Particularly important was the conception of electrical equipment and cables which could be grossly overloaded without risk of fire to assist in the safe return or landing of the aircraft under conditions of severe damage or engine failure. The author was especially concerned for the development of new forms of constant speed drives for the frequency conversion for instrument and radio, and of exhaust turbo-alternators, and welcomed the interest expressed in these projects.

Mr. W. H. Campbell (Metropolitan Vickers).

He agreed it would not be desirable to take a size of aircraft such as 40,000 lb. A.U.W.

as the lower limit for adopting A/C. The advantage of the new system would be the more apparent in medium and large types with four or more engines, but there would almost certainly be a tendency to spread this system down to much smaller aircraft as the weight saving and general suitability became more apparent.

In regard to the effect of heavy short time loads on voltage regulation to other services, it would be generally more advantageous with four engines to subdivide the loads rather than force the steady load services to accept momentary changes in pressure, except when emergency conditions necessitated the switching of these loads on to the generators which supply the intermittent loads, which may be considered as part of the margin of spare capacity.

W/Cdr. M. J. Smith.

In regard to the possible 120 volt D/C system he noted that whatever may be said in its favour the drawbacks due to continued use of commutators and difficulties of transforming voltage for lighting largely discount it as a serious rival to the new A/C system. Hence it was preferred to deal with this matter in discussion rather than to give space in the text of the paper.

As to the merits of paralleling, his conviction stood that this was neither necessary nor desirable when four separately driven generators of adequate capacity were provided. The additional cables for alternative supply did not as was visualised, entail much unnecessary duplication of cables, since the motor would so far as possible be located somewhere between the alternative generators so as to obtain supply from either direction. There would, in consequence, be no appreciable increase of voltage drops.

In regard to parallel working of generators he wished to emphasise that the recommendation for sub-division of loads was not to avoid admitted difficulties in paralleling, but on grounds of definite technical and operational preference for individual working where not less than four generators are provided. For example, the number of services experiencing disturbed supply conditions due to automatic switching on any one generator going out of action, was considerably reduced as compared with the wide effects of the temporary disturbance due to a heavy fault on a parallel system, and the margin of generator capacity over average load incidence was spread over the sub-divided system so as to minimise the overload conditions suggested by automatic load transference if a generator stopped. Moreover, experience had shown that such faults as occur were nearly always open circuits rather than short circuits.

As mentioned elsewhere, an important reason for wishing to avoid constant speed generator drives on all engines was the modest amount out of the total power which was required to be so closely controlled.

As regards excitation for alternators, the view was held that commutator excitors should be avoided for the reasons already made clear, and hence schemes based on rectifiers with or without initial battery supply for excitation were being developed.

Mr. F. Butcher (Rotax Limited).

The relative merits of high and low impedance earthing of the generator neutral would no doubt be resolved by experience gained in the near future, but it seemed preferable now to start in the simplest possible way with the knowledge that earth faults were less likely than open circuits.

It was agreed that earth fault indication with fault limiting impedance and optional clearing of the faulty circuit formed an attractive arrangement.

The views expressed on the possibilities with small 2 pole motors were welcome and stimulating, but it was felt that more experience with 24,000 r.p.m. on such machines was needed for any general adoption of this type.

Mr. R. H. Chaplin (Hawker Aircraft).

The questions raised were those naturally expected from the aircraft designer at this

stage, and more such questions would be welcomed. Conditions in the last few years had emphasised the need for electrical development, and at the same time, unfortunately, driven it along the less favourable line of direct current owing to war-time impossibility of effecting a major change in system; but the whole picture of future possibilities had now changed with the advent of the simplified alternating current supply at higher volts and high cycles. It was clear from the experience of Mr. Chaplin and others, that in perfecting the pure and simple electrics of the auxiliary services, the ever-present necessity for full reliability in the mechanical aspects must be kept in mind. The important matter of the relative complexity of the complete hydraulic and electric installations had been illustrated in the slides used after the discussion.

Mr. G. W. Mullett (*Short Bros.*).

The contribution in the application of electrics to aircraft, particularly flying boats, by Short Bros., was well known and considerable, and the views expressed as to the practical limit of size for D/C installation and battery weights were noteworthy. Although the boat plane would require some special consideration in the general development of the variable frequency A/C system, this was not likely to differ fundamentally from an installation for a land plane of comparable size and equipment. The neutral point of three phase alternators being connected to the airframe was not primarily intended to carry out of balance currents, but to limit the leakage or shock potential of the installation, thus enabling a more economical voltage to be used with safety than was adopted for the Shetland.

On the question of standardisation, Mr. Mullett's recognition of the possibilities of grouping in the design of actuators was significant, and the noteworthy efforts of the S.B.A.C. in standardisation would doubtless be so applied as to achieve the desired economy without hampering development.

Mr. I. O. Hockmeyer (*M.A.P.*).

It was clear that Neville's investigation was a necessary preliminary to the now agreed introduction of the 200 volts 400 cycles system, and expediency played a large part in its selection. This included ease of conversion to other voltages for instruments, radio, and lighting, so as to avoid different generators in tandem. He was glad Mr. Hockmeyer also agreed with the proposal for high speed gas turbo-driven alternators for the future.

Mr. F. P. Wills (*R.A.E.*).

In an extension of the D.C. system, both as to voltage and power, even if brushes did not wear quickly, commutators would still be a limiting feature in the improvement of design, performance and maintenance, and this fact tended to be brushed aside in the liking for the characteristics of D/C motors. The diversity of these characteristics also tended to defeat standardisation to any useful degree.

In British aircraft alternators it was proposed to avoid excitors with commutators. The running of auxiliary generating plants at altitudes needing supercharging was not recommended.

In regard to complexities in distribution systems, the author preferred the greater simplicity which should be obtained with independent A/C generators having relatively high overload capacities. The adoption of a W type of system was thereby envisaged instead of distribution from a central switchboard with redoubling of cables as required with generators in parallel. The margin of generator capacity with light weight alternators would minimise complications in switching of loads to an alternative generator if one went out of action.

It was concluded that on the whole the varying frequency system, as now approved by the Ministry, offered the simplest arrangement, as seen at present, for the widest variety of aircraft.

MODERN EXPERIMENTAL WORK ON AEROPLANE STRUCTURES

by

A. G. Pugsley, O.B.E., D.Sc., M.I.Struct.E., F.R.Ae.S.

Dr. A. G. Pugsley was head of the Structural and Mechanical Engineering Department, R.A.E., from 1941 until his appointment in 1945 as Professor of Civil Engineering at Merchant Venturers' College, Bristol. Trained at the Royal Arsenal, Woolwich, he took his B.Sc., London University, in 1923, and his D.Sc. in 1938. From 1926-31 he was at the Royal Airship Works, Cardington, and in the latter year joined the R.A.E. He was a member of Council 1940-43, and was awarded the O.B.E. in 1944.

A MEETING of the Society was held in the lecture hall of the Institution of Mechanical Engineers at Storey's Gate, St. James's Park, Westminster, London, S.W.1, on Thursday, April 5th, 1945, at which Dr. A. G. Pugsley, F.R.Ae.S., presented a paper entitled "Modern Experimental Work on Aeroplane Structures."

In the chair, the President, Sir Roy Fedden, F.R.Ae.S.

THE PRESIDENT: Dr. Pugsley had commenced his professional career as a Student Apprentice at the Royal Arsenal, Woolwich, in 1923. In 1926 he had become a Junior Technical Officer on Research and Design at the Royal Airship Works at Cardington; and in 1931 he had become a member of the Airworthiness technical staff at the Royal Aircraft Establishment. Since then he had worked at the R.A.E. on a wide range of subjects. He was one of the outstanding men of the younger generation in British aeronautics, and his progress had been to such good purpose that he was at the moment Head of the Structures and Mechanical Engineering Department at the R.A.E.

The President was of opinion that Dr. Pugsley's greatest achievement was the work he had done some years ago on flutter. In that work he had interpreted the heaviest mathematics of that complex subject in a rationalised form, enabling the ordinary mortal to understand the subject and make use of his work.

Apart from his official duties at the R.A.E., he had been during the last two years Chairman of an important and confidential Committee of the Society, doing work of national importance; he was also serving on two or three of the sub-Committees of the Aeronautical Research Committee.

Quite recently he had been elected to the Chair of Civil Engineering at Bristol University, and he hoped to take up his appointment there shortly after the war.

MODERN EXPERIMENTAL WORK ON AEROPLANE STRUCTURES

Introduction

WHEN I was invited to give a lecture on structural testing, I accepted only after considerable hesitation. For a long time now I have had little opportunity for doing any experimental work myself, and I realised that I should find myself talking largely of the work of others, in some cases without a really close knowledge of the experimental details. Two considerations, however, swayed me in favour of attempting such a lecture. Firstly it happened that I had just been preparing a paper on the history of structural testing[1] for the Institution of Structural Engineers. This paper covered in outline experimental work on structures of all kinds over the period 1700 to 1940; and it struck me that a survey of modern experimental work on aeroplane structures, including so far as possible present-day work, would form an interesting companion to my earlier paper. My second consideration was more important: it was that during the greater part of the present war I have had the good fortune to lead at the R.A.E. a department that has dealt with a greater volume and variety of experimental work on structures than has been the lot of any such unit in this country hitherto. If, therefore, I could by a survey of this work present a picture of what modern experimental work on aeroplane structures is, and looks like becoming, and so provide a broad basis from which to look more closely at any particular aspect of the work on some later occasion, I should have done a job that would be useful and not inconsistent with my own part in the matter. That is my main aim here.

I cannot properly start a lecture to this Society on structural experiments without referring to some earlier lectures, particularly those[2, 3] by Mr. I. J. Gerard. It is impossible to look back at his lectures, delivered over the period 1930 to 1932, without being impressed with the advance that they represented and the amount which current work owes to Mr. Gerard and other members of the old Mechanical Testing Department of the R.A.E., so long led by Dr. W. D. Douglas. I am tempted also to look back a little further to the large-scale laboratory and flight work described by Col. Richmond in a lecture[4] on airship experiments, given to the Society in 1926. I hope in the course of the lecture to bring our modern work into a longer term perspective by occasional examples from these earlier papers.

One's perspective can, of course, also be widened by considering experiments in the field of structural engineering generally, the relevance of which lies in the technical similarity of many of its problems and techniques. Dr. De Bruyne once sent me a postcard of the Britannia Bridge with the remark that it was the first stressed skin structure, but it happened that I had already become aware of the point by reading an account of the many experiments conducted by Stephenson and Fairbairne on a variety of tubes in bending and shear as a basis for the design of the bridge. Another example relates to the torsional instability of struts, a type of failure that is complicating the design of stringers at the present time. It happens that this type of failure was well known to airship constructors nearly thirty years ago, when tests on Zeppelin bracing members were habitually presented by strut curves with portions of their lengths marked "torsional instability" or "failure by twisting." The traffic in ideas is not, of course, always one way. It is evident that at the present moment the idea of test frames

[1] A. G. Pugsley: The History of Structural Testing, *Journal of the Inst. of Structural Engineers*, Dec., 1944.

[2] I. J. Gerard: The Primary Importance of Mechanical Testing in Aircraft Construction, *Journal of the Roy. Aero. Soc.*, July, 1931.

[3] I. J. Gerard: Mechanical Tests of Aircraft Structural Components, *Journal of the Roy. Aero. Soc.*, Sept., 1932.

[4] V. C. Richmond: A Review of the Present Position with Regard to Airship Research and Experiment, *Journal of the Roy. Aero. Soc.*, 1926.

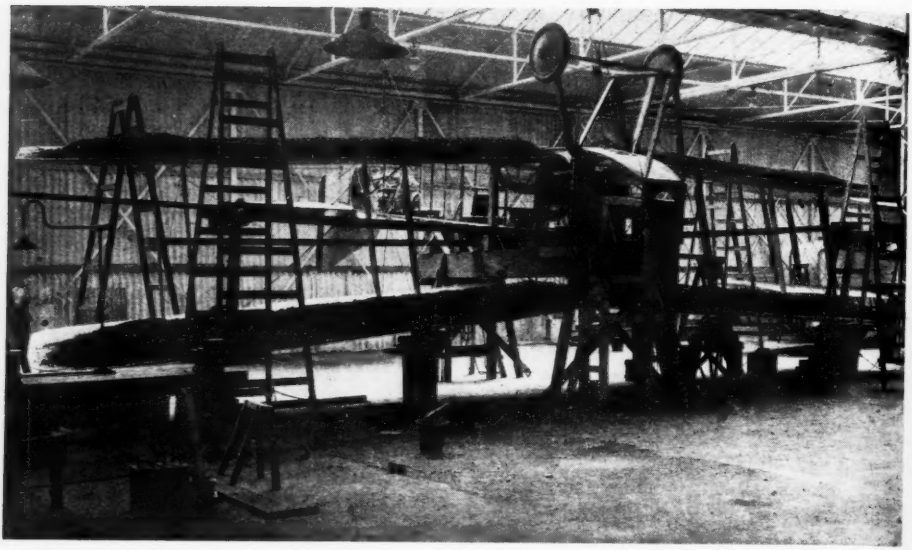


Fig. 1

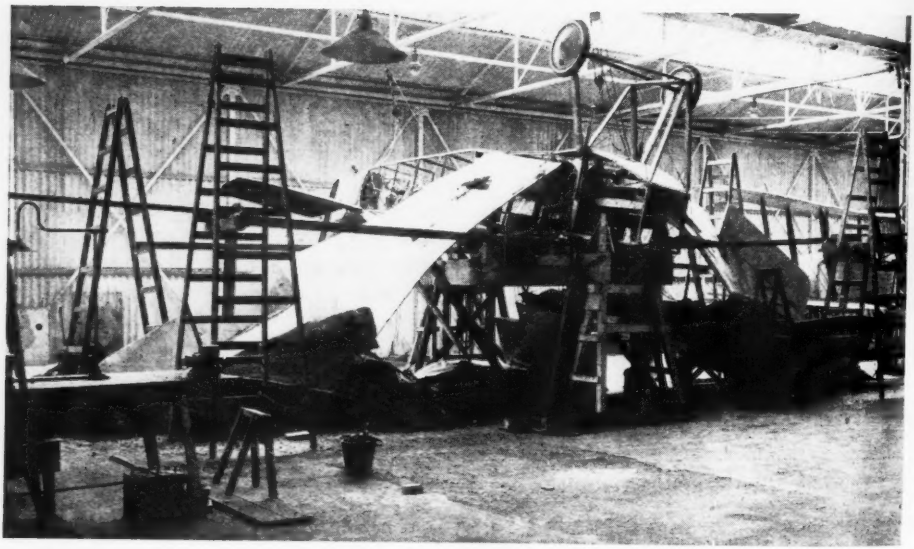


Fig. 2

as distinct from testing machines is likely to pass out from the aeronautical world to the structural world generally; so also are our large-scale uses of wire resistance strain gauges, though the armament world can there, perhaps, claim some priority. These are all examples of one single point: that in this experimental field it is always wise to remember that our activities are an aspect of wide general structural ones, and that there is much to be gained by freedom of contact between workers throughout the whole field of structural experiment. Too often, I think, in the past has one section of this large community, be it associated with building construction, shipbuilding, or with aeroplanes, been content to work without contact with, or knowledge of, what the other is doing. The war has done much to break down such insularity, and has at the same time placed a special responsibility upon aeronautical workers, who are in many ways now the leaders in this structural field, to see that their methods and experience become available to others.

Laboratory Work on Complete Aeroplanes and Large Components

It is natural for any member of the R.A.E., when considering structural experiments, to think first of major strength tests on aeroplane wings and fuselages. Most of these tests, in the early days when aeroplanes were small and relatively weak, were conducted by the gradual addition of dead weight. For tests on wings, the aeroplane was supported at the centre section in the inverted position, and sand or shot bags distributed along the wings until failure occurred. An early test of this sort is illus-

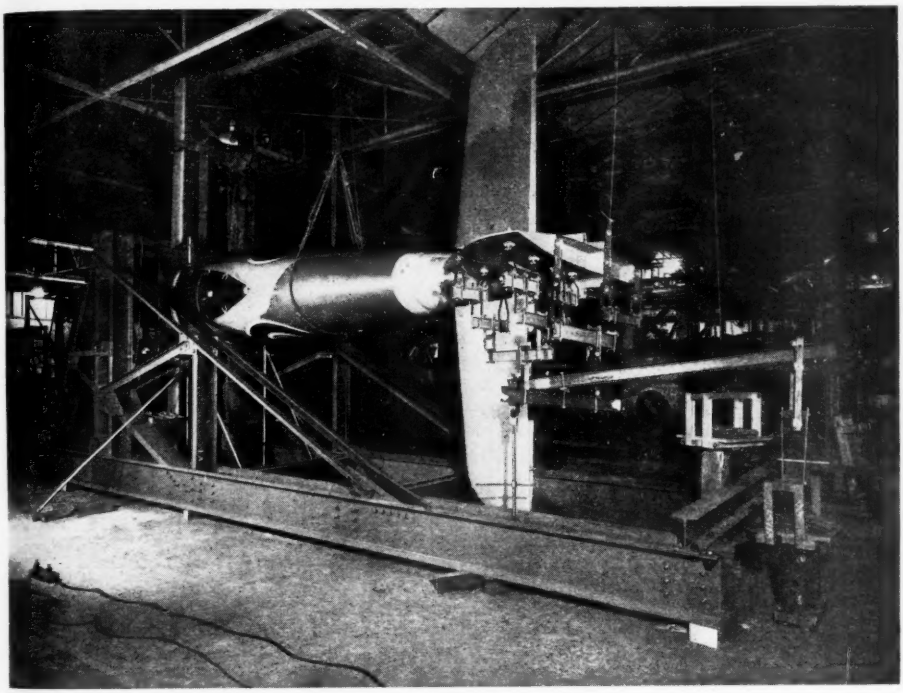


Fig. 3

trated by Figs. 1 and 2, which show incidentally two of the disadvantages of dead weight methods of test—the inaccessibility of the surface of the structure for inspection whilst under load, and the liability to complete wreckage of the structure following a failure of any sort. These two considerations, together with the increasing difficulties and inaccuracies arising from direct loading by sand or shot as wing loadings increased, were very much in the minds of those concerned with developing the early strength-testing frames; and with the development of stressed skin construction the first point regarding accessibility for inspection became, of course, increasingly important.

The first test frame built for wings was that designed by Gerard and erected at Bristol for experiments on a multi-spar wing constructed by the Bristol Aeroplane Company. It was later re-erected at Farnborough, where it has become known as the Temple and has been used for many wing and fuselage tests. The essential idea was to provide a stiff base of structural steelwork to which the root of a wing or fuselage could be firmly attached whilst loads could be applied to other parts of the specimen by jacks through suitable levers and links, the whole system of loads and reactions being self-equilibrating within the test frame. Loading through links—though there might be a forest of them—made inspection possible, and the use of screw or hydraulic jacks got rid of much of the final wrecking caused by the "carry through" of dead weight loading. The only limit to the magnitude of loading possible was now not the height of the pile of sand or shot bags, but the local and overall strength of the specimen itself. Modern tests in this type of frame are illustrated by Figs. 3 and 4, the first a fighter fuselage test in a small frame on the pattern of the Temple, and the second a fuselage

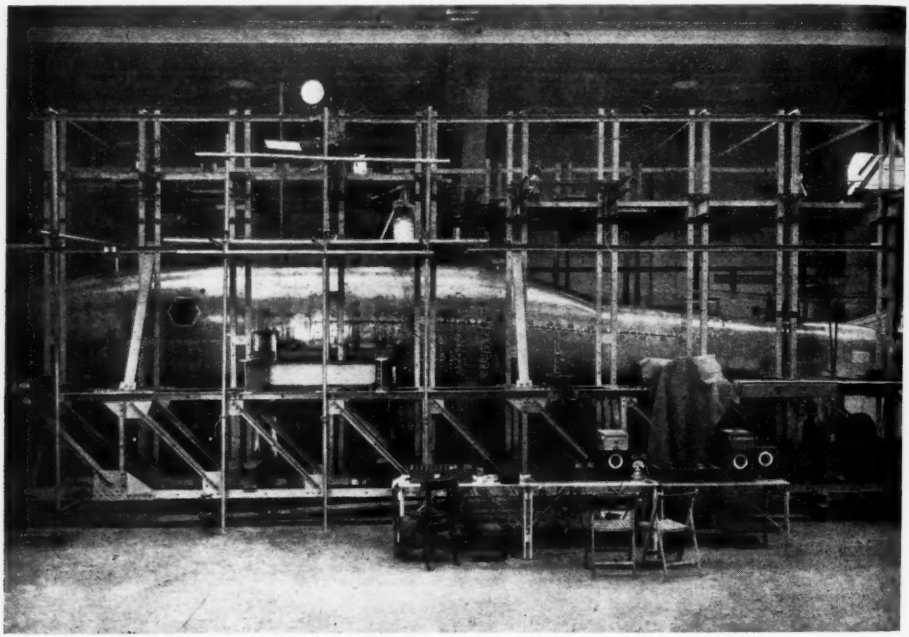


Fig. 4

test on a rather larger aeroplane in the Temple itself, as it now appears after miscellaneous additions and modifications. You see in Fig. 4 a pointer to one of the limitations of the early idea. It is now frequently unsatisfactory to hold a fuselage by cutting off its forward end and fixing it rigidly to a "wall." Instead, an attempt is made to hold the fuselage, as it is held in reality, by the fuselage centre section. In fact, in wings the stress distribution at the root is particularly sensitive to the way in which the reactions are supplied, and the "wall" type of fixture may be far from representative of the fixture provided in practice by the fuselage. The testing of wing tip-to-tip specimens that this calls for does not present any special difficulties once space is available,

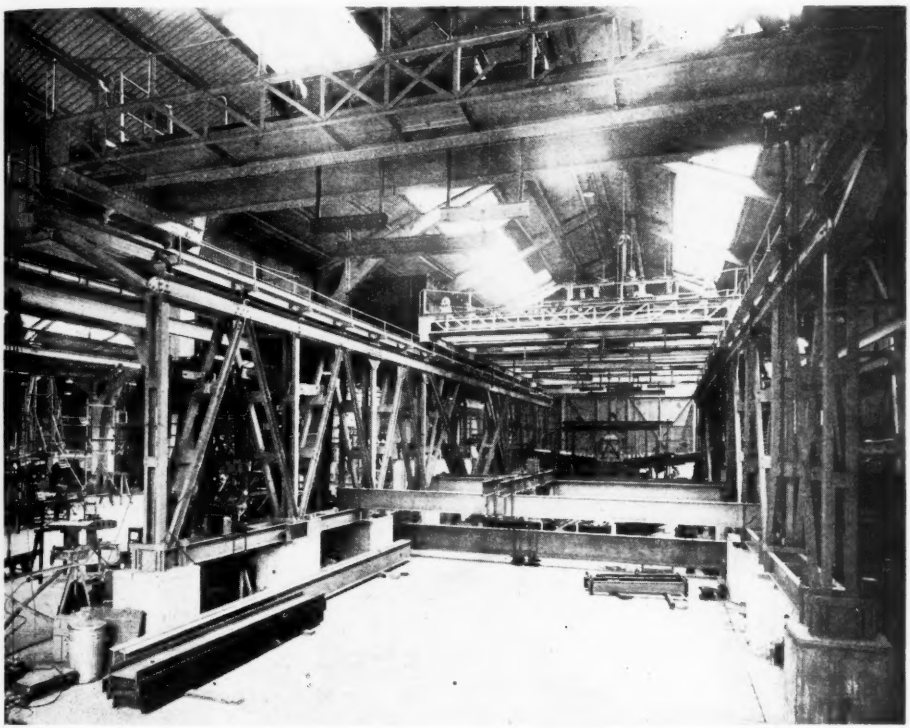


Fig. 5

wing roots. In Fig. 4 this is done by girders acting as a dummy wing centre section, but it is frequently possible to use the wing centre section proper. This illustration incidentally shows wire resistance strain gauges in use around openings and at other points of interest.

Just as fuselages are best held by the wing centre section, so wings are best held by the but there is a further point arising to a special degree in wing tests. It is the magnitude of the deflections arising before failure. In modern wings, tip deflections are to be measured in feet where the corresponding fuselage deflections are only a few inches. Every improvement in the strength of structural materials, so long as it leaves untouched the basic Young's modulus

values, exaggerates these deflections. Two related difficulties arise in a test frame—one the matter of head room to provide free space for the deflections, and the other the swinging of the loading links out of the vertical as the deflection takes place. In the R.A.E. type of frame the simplest answer is, of course, to provide more head room to meet the former difficulty and minimise the latter.

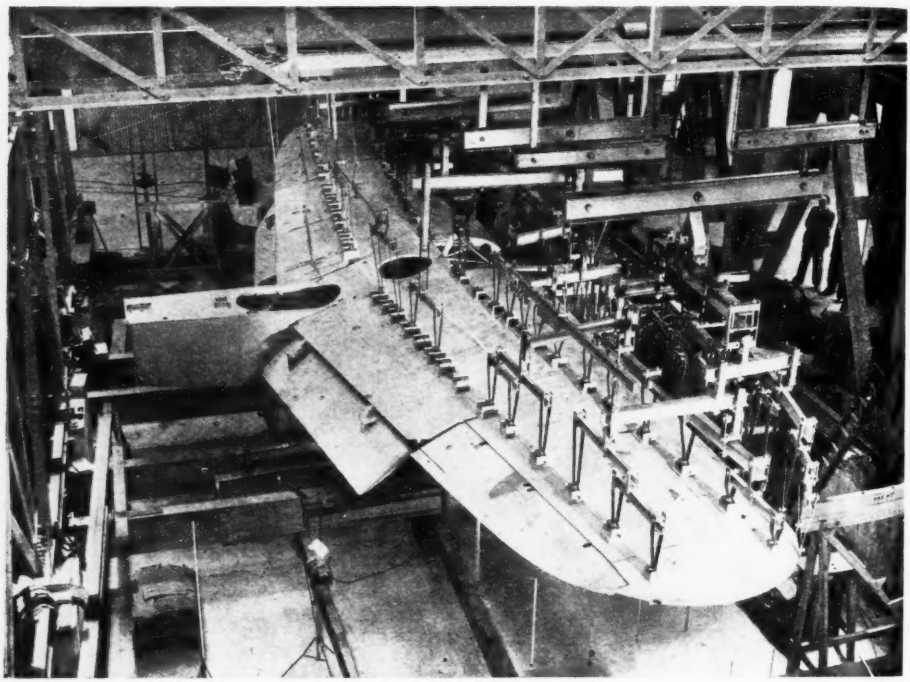


Fig. 6

These considerations lead to a frame of the type of the "Cathedral," now in full use, though still being "mechanised" and equipped with instruments. This frame, which is illustrated generally by Fig. 5, and is in use for a wing test in Fig. 6, has been designed largely by F. Alexander as a result of the experience gained first by Gerard and more recently by Hotson. I do not intend to describe this frame in any detail—I hope that will be done on its completion by those more directly concerned—but I might just remark on its broad method of functioning in the case of a wing test. The tip-to-tip specimen is held down to the reinforced floor by the fuselage centre section while the wings are pulled upwards through a link system like that shown in Fig. 6 by straining units in the overhead bridges. Straining is by screw gearing, whilst the balancing out of the initial dead weight of the link system, etc., and the measurement and control of the applied loads is done hydraulically. Eventually the gearing will be operated electrically from the central control room just visible above the main girders on the left in Fig. 5, where the hydraulic system will also be brought to a central control and measuring unit like that of a modern hydraulic material testing machine. Cen-

tralised equipment for the recording of wire resistance strain gauges will be installed in the same room.

Whilst we are considering Fig. 6, I would make a point that is of general importance in the matter of wing and fuselage testing. The number of links and pick-up points in Fig. 6 is nowhere near so numerous as in some earlier tests in the Temple. It became clear from the earlier work—and more particularly as a result of discussions with Mr. B. N. Wallis of Vickers some years ago—that as it was not possible by even a forest of links to represent properly the detailed mode of application of the aerodynamic pressures and suctions and of the inertia forces that make up the load in practice, we should aim in major tests of the type here considered to represent primarily only the bending, shear and torsional actions at each section of the specimen. We thus leave such details as the effect of transverse pressures on local panels and attachments to be the subject of a separate test. Hotson has, however, tried with some success to combine a detail test with the major one. In one case the inside of a wing was rendered pressure-tight and, whilst the wing was under load in the frame, air pressure was applied inside to represent the external suction present in flight; it was interesting to see how the pressure "smoothed out" the buckles present in the skin due to the general loading. He has also experimented with a "suction box," shown in Fig. 7, placing it over a few panels of the wing surface and then exhaust-

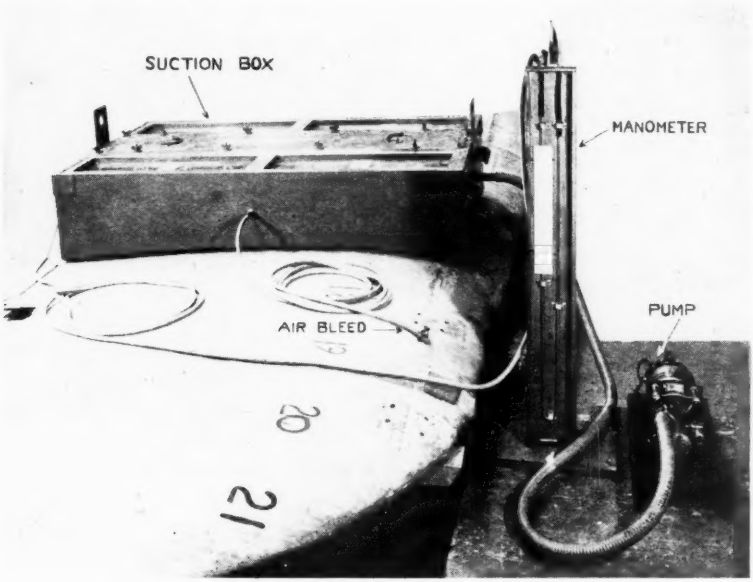


Fig. 7

ing the air from the inside. A difficulty here is that the wrinkles of the skin of a modern wing become so pronounced at high loads that too much leakage would develop around the edge of the box.

This wrinkling of a modern wing is well illustrated by Fig. 8, which shows the upper surface of a large wing at two stages of loading (100 per cent. load corresponds to the specified ultimate strength). I have chosen this particular example because it happens to illustrate the wrinkling that

occurs in a wing with a cover reinforced with heavy corrugated sheet, and with little in the way of spar booms. This approximates to a form of construction in which a number of British designers are now interested, and you will see from the " close up " of the surface (Fig. 9) how the wrinkles at high loads mingle with the inter-rivet buckles and so "worry" the rivets.

This leads me to a point in which I am particularly interested at the present time. so under repeated loading. We are therefore not only " mechanising " the Cathedral so that the proof load, say, on a large wing can be applied, if desired, a hundred times in a day, but are conducting some preliminary repeated loading tests on a series of tailplanes. Fig. 10 shows what has happened to the rivets at the root of a tailplane after a large number of repetitions of a moderate load; you will see how the countersunk rivets have lost their heads!

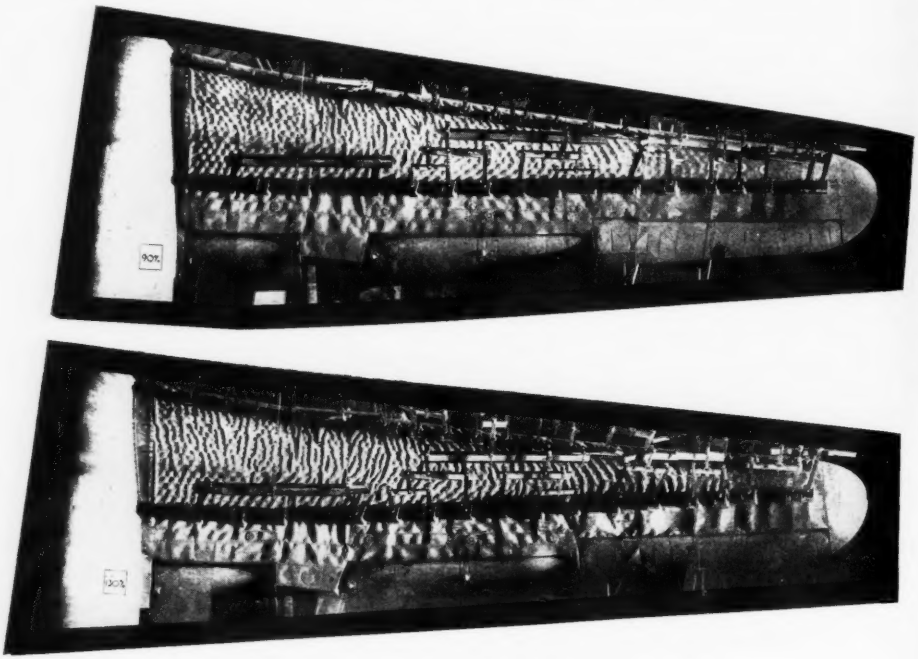


Fig. 8

It is apparent from Fig. 9 that repeated application of loads to produce such wrinkling might very well break off the heads of the countersunk rivets; spot welds might suffer even worse. With the move towards smoother wing surfaces, moreover, and the resulting natural use of thicker skins, the problems of stress concentrations at main attachments and of inter-rivet buckling becomes more important, and both the more

I cannot leave the subject of laboratory work on complete aeroplanes without some reference to stiffness tests and resonance tests. Since the early work on these, in which I participated, a number of improvements have naturally been made, particularly in the field of resonance testing. Here Squadron-Leader Fiszdon has with Moffat greatly developed the vibration measuring and recording side by means of induction

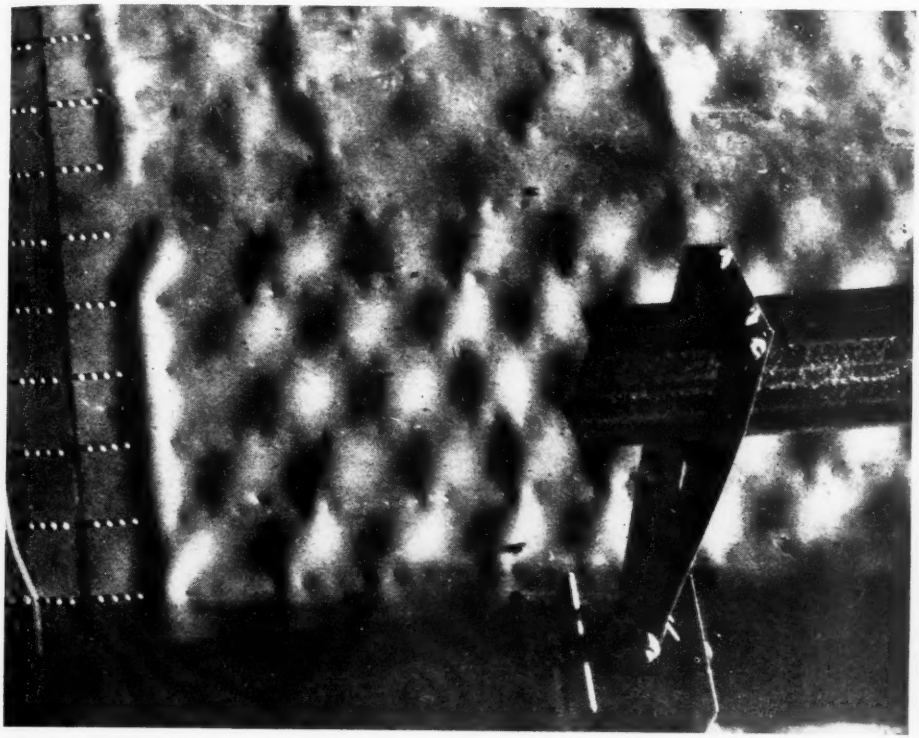


Fig. 9

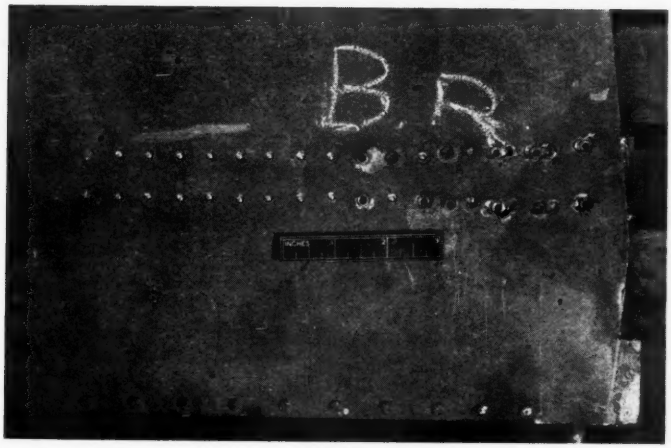


Fig. 10

pick-ups and oscillographs. Whereas before the war our simple manual methods gave us a knowledge of the first three natural modes of a wing, but with little indication of what the fuselage and tail were doing at the same time, we are now able to plot full pictures of the aeroplane motion as a whole for the first five modes. Fig. 11 illustrates the nodal lines (in plan view) for the first four natural modes of a fighter.

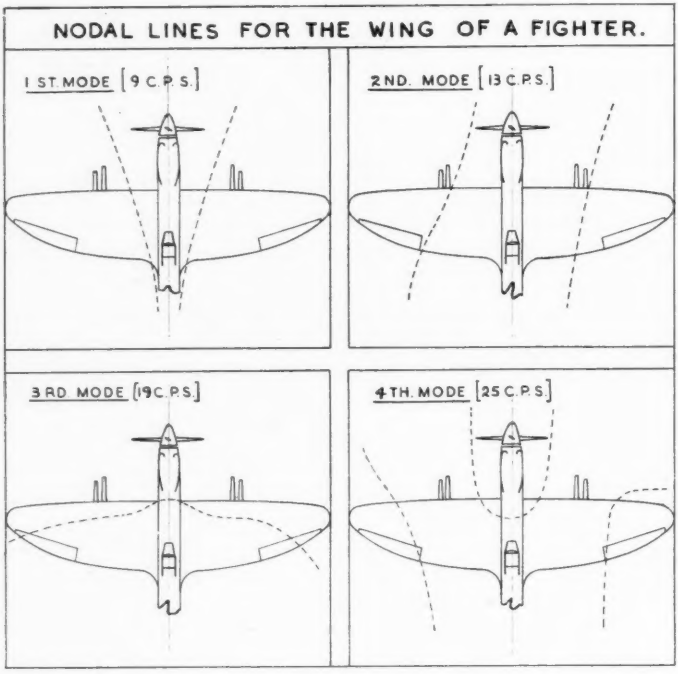


Fig. 11

This brings me to the conclusion of my remarks on large-scale testing with a point for the future. The number of fatigue fractures occurring in aeroplane structures appears to be on the increase, particularly in tail components. Whether this is due to the increasing power of engines and propellers without a counterbalancing reduction of degrees of out-of-balance, or due to the perhaps poorer fatigue-resisting qualities of the newer materials, one cannot say with certainty, but it is evident that more fatigue testing of both materials and structures is desirable. The design of equipment for the fatigue testing of a structure will present considerable difficulties; one can visualise the final rig as representing either a developed form of repeated loading test or a severe form of resonance test. The matter calls for considerable experimental exploration, I suggest in the first instance with tailplanes, including their root fittings. The only recent attempts at tests of this sort made at Farnborough were on some tailplane spars and root fittings, which were tested in the manner of a resonance test, calibrated by reference to full-scale amplitudes of deflection and local strain gauge readings. The procedure was reminiscent of the old vibration tests on ribs, though direct calibration against flight conditions was not practicable in those days.

Laboratory Work on Small Components and Research Specimens

With the transition from biplanes to metal-covered monoplanes, it was obviously desirable to establish some sort of sample component test that would replace the old sample spar tests. The compression panel test with which we are all familiar to-day resulted from an extensive series of experiments by Gerard[5] with the above aim in view, during which some very useful methods of testing panels and cylinders representative of stressed skin structures were developed.

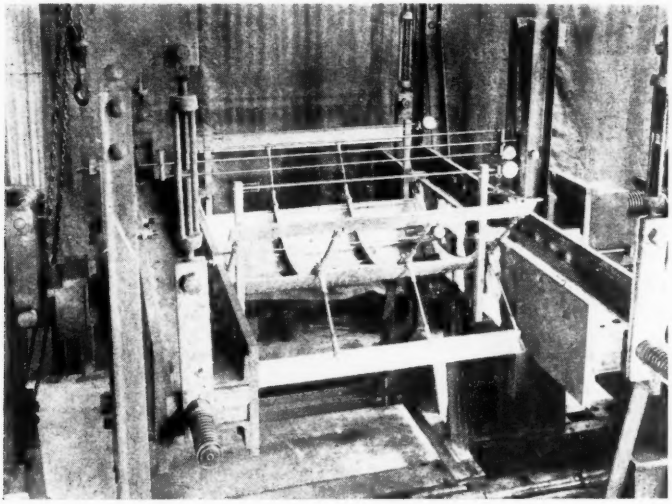


Fig. 12

At the time that Gerard started his panel tests, criticism and debate tended to concentrate on the conditions to be imposed upon the free edges of the panel between the plattens of the testing machine. By a great deal of work he convinced most of us that, provided the panel was several stringer spacings in width, these edge conditions were not very important. We have since tended to become rather more fussy in this matter, and the present standard research habit is to use stabilising combs along these otherwise free edges. It is interesting to compare this arrangement with some of the early more elaborate panel tests made by Gerard (Fig. 12).

During the last year or so, however, attention has been concentrated more on the conditions imposed upon the loaded ends of the panel. More accurate measurement of the overall deformations of panels has indicated that in most conventional testing machines—designed, of course, primarily for material testing—the plattens do not remain sufficiently parallel to each other during a panel test, and they also show a tendency to shear sideways relative to each other. These effects are, of course, particularly noticeable and important during tests on panels that are wide in relation to the plattens and approaching in strength the limit of the testing machine. With the present tendency to thick metal skins with closely spaced reinforcement, the standard panel test is becoming a heavy job, and the difficulties arising with existing testing

[5] I. J. Gerard and B. G. Dickens : Stressed Skin Structures. Compression Tests of Panels with Tubular Stiffeners, R. & M. 1830 (1938).

machines are emphasised. One way of trying to overcome these is to use a testing machine designed for much heavier duty than required by the panel and with plenty of space to spare around the panel in which to build up suitable load and strain controlling rigs. H. L. Cox has recently explored this approach at the N.P.L., inserting a load distributing pyramid of structural steel girders between the top of the panel and the upper platten of the machine.

combined compression and torsion, with internal pressure as well if required. Fig. 13 shows one of a series of box tests now in progress at the R.A.E. In this figure the specimen is rigged in a 100-ton horizontal testing machine so that it can be subjected to axial compression and torsion, simultaneously or separately. The strain gauges, only the leads to which are evident in the picture, are in this case on the stringers, sheet and frames inside the box. These tests, and the

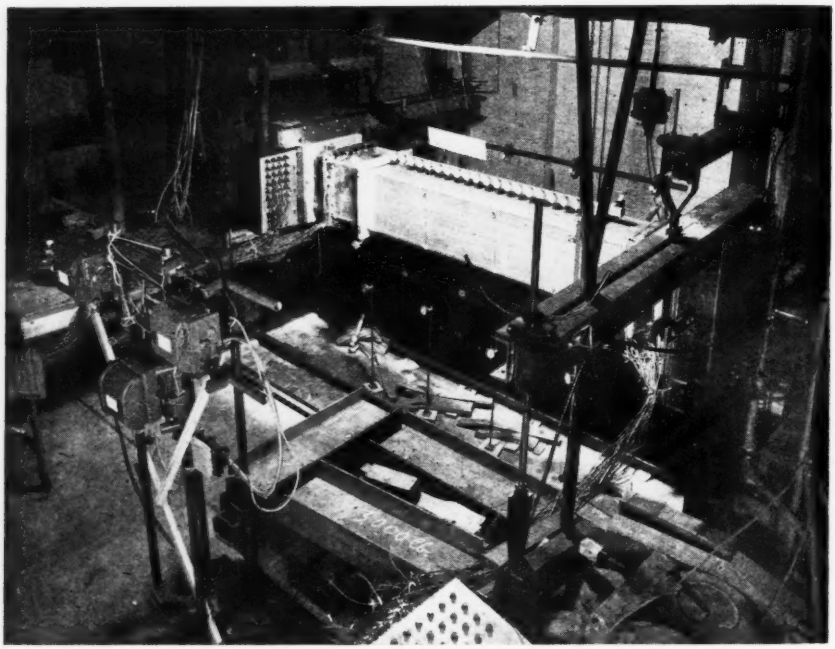


Fig. 13

It may be, of course, that more appropriate testing machines can and should be designed, but another way of dealing with the matter is, for accurate work, to abandon the panel test and return to cylinder or box tests. Such specimens, whether tested in a machine or special test frame, simplify the problems of securing appropriate and known loading and boundary conditions, and at the same time make possible tests under

much larger one illustrated by Fig. 14, have been arranged in conjunction with the Bristol Aeroplane Company. The box in Fig. 14 was tested in compression in the 1,250-ton horizontal Avery machine belonging to Messrs. Dorman Long. The type of failure obtained (Fig. 15) is indicative of the new emphasis to be placed on rivets and their spacing.

It is convenient here to say a few words

on the use of wire resistance strain gauges in laboratory work on structures. There is, of course, a great temptation to use more gauges than one is capable of analysing and understanding, but granted that a large number is often desirable, the handling of the resulting work presents a real problem. The laborious way, and one that seems best for numbers of gauges up to a hundred, particularly on research jobs, is to read each gauge in turn at a given stage of loading by switching manually from one to the other and noting each down. Equipment of the kind needed for this is shown in use in Fig. 4. For dealing with several hundred gauges, Mr. E. Jones and Miss Pellew have, in conjunction with Messrs. Tinsleys, developed equipment by which each gauge signal is recorded by an ink pen on paper in the manner of a barograph, the switching from gauge to gauge being done automatically at the rate of a 100 in about three minutes. Fig. 16 illustrates a 200 gauge unit of this kind now under development for installation in the control room of the Cathedral. An alternative method is to switch the gauges in and out of cathode oscillographs, the signals being recorded on a high-speed photographic film. This method has special merits for flight work, but it may also be of value in the laboratory. Comparable equipment, with very different gauges (actually of spark gap type) was used at Cardington twenty years ago.[1]

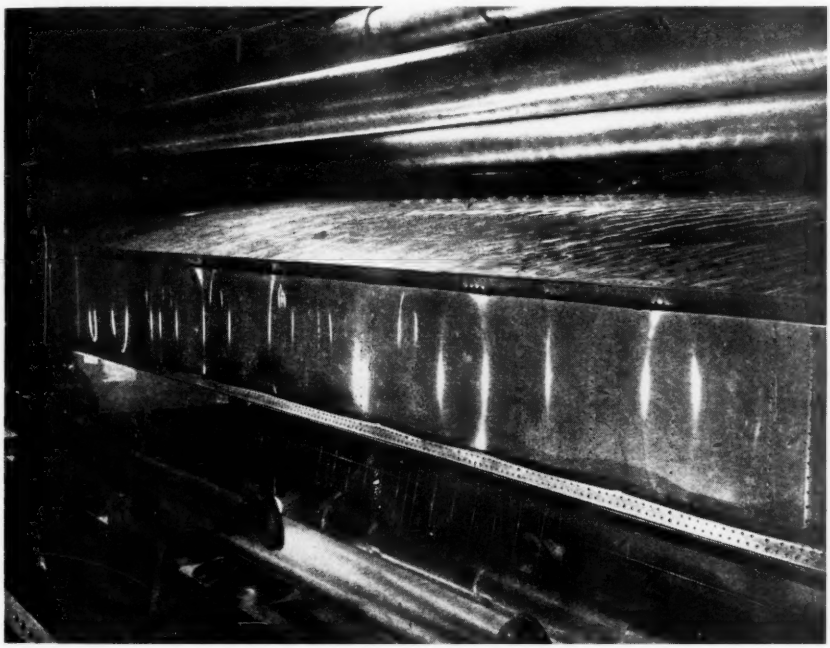


Fig. 14

The spirit of criticism that has led to the current interest in box tests has led also to an attempt to understand better the behaviour of structural joints under load. Curiously enough, in the matter of the behaviour of riveted and bolted joints, and even welded joints, under static and repeated loads, aeronautical knowledge is in some ways behind general structural knowledge, which in recent decades has been greatly advanced

by the activities of the Steel Structures Research Committee[6] and of the Welding Research Council. On the matter of the behaviour of riveted and bolted joints under gradually applied loads, Professor Vogt, of Trondheim, has recently prepared for us an excellent summary of existing information[7] and has designend a series of critical tests, now in hand, to establish a theoretical treatment of such joints, allowing for plasticity. with similar scale tests on their joints. We are therefore planning at Farnborough for a new large testing machine of somewhat unconventional design that shall be capable of static and repeated loading tests on the largest spar boom joints at present contemplated.

Associated with the non-linear behaviour of joints is the problem of structural damping. It is well known that the damping in

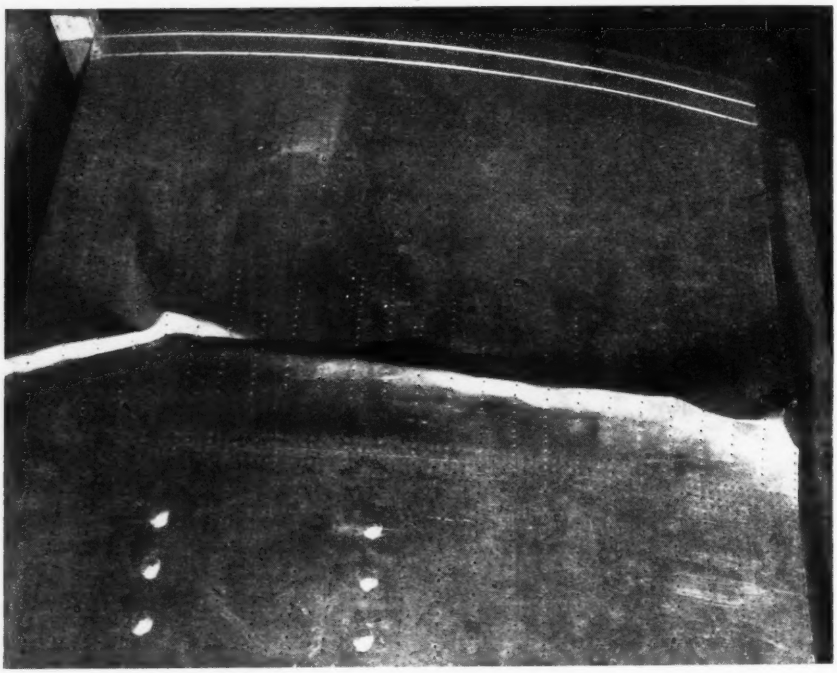


Fig. 15

In many respects experimental work on joints is an area of work where material and stressing problems become more than usually intermingled, and however satisfied we may be with model scale tests for the design of large structures, we shall be less satisfied a structure (commonly measured during a wing resonance test) is usually very much higher—perhaps fifty times as high—as the damping inherent in the material of the structure. This damping associated with riveted and bolted joints has arrived in our structures by accident, as it were, but what if we really tried to introduce damping—with an eye, perhaps, to the suppression of flutter or other vibration? We are doing a few experiments on this possibility at the present

[6] First, Second and Final Reports of the Steel Structures Research Committee, H.M.S.O., 1931, 1934, 1936.

[7] F. Vogt : The Load Distribution in Bolted and Riveted Joints in Light Alloy Structures, R.A.E. Report No. SME. 3300 (unpublished).

time—Fig. 17 illustrates one of these, in which the damping of a built-up tubular beam is being measured. One has, of course, to realise that damping in a joint implies relative motion of a non-linear character and must therefore be considered in conjunction with other advantages and disadvantages of "give" in joints. The wholesale adoption of welded joints naturally eliminates "give" and might lead—as I believe it did in certain early welded bridges—to stress concentration and resonance difficulties customarily avoided (without special forethought) by our use of rivets and bolts.

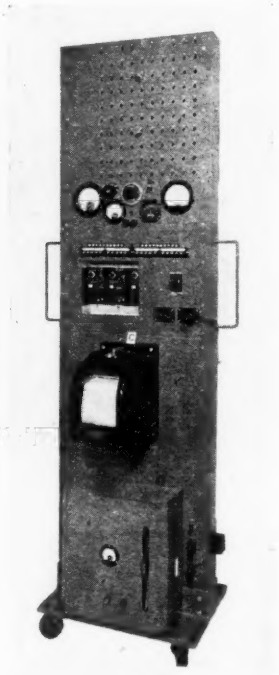


Fig. 16

Model Work

Some of the testing work discussed under the preceding heading in relation to small components can, of course, alternatively be regarded as model work, but what I have in mind here is model work of a rather more extreme kind, typified by rubber model and photo-elastic experiments.

From quite early times engineers have turned to rubber models as a means of studying the general behaviour of structures under load, but when Professor Sutton Pippard started his experiments on plane stress problems by measuring the deformations of thin rubber sheets floated on mercury,[8] he placed the work on a new level of quantitative accuracy. At a later date D. Williams initiated a further series of experiments[9] (again on plane stress problems such as the stress distribution around holes and notches) in which the apparatus used was cruder, but with which he was nevertheless able to obtain quickly results of sufficient accuracy for many engineering purposes. So far as I am aware, neither of these methods has been used as generally as one might have expected.

Spread over the last twenty years or so, comparable experiments have been made using various plastics such as celluloid and xylonite for the models. This work also has, until recently, tended to be restricted to two-dimensional work, primarily in the field of frameworks. In its more accurate form it was initiated by Professor Beggs, but Professor Sutton Pippard later developed a simpler technique using larger deformations.[10] Recently this area of work has been further widened by its application to three-dimensional structures, frameworks and otherwise. Dr. Redshaw and Mr. Arthur of Messrs. Boulton Paul have now applied it to a variety of stiffness problems, using

[8] L. Chitty and A. J. Sutton Pippard: On an Experimental Method for the Solution of Plane Stress Problems, *Proc. Roy. Soc.*, A, Vol. 156, 1936.

[9] D. Williams: Note on a Suggested Method of Using Rubber Models for Stress Investigation, R.A.E. Report No. SME. 3122 (unpublished).

[10] A. J. Sutton Pippard and S. R. Sparkes: Simple Experimental Solutions of Certain Structural Design Problems, *Journal of Inst. of Civil Engineers*, Vol. 4, 1936-37.

measurements on a xylonite model, proportioned by dimensional theory, for the estimation of the stiffness of a complicated structure. We have tried this approach in some simpler cases, and also begun to explore the possibility of using such models for stress distribution as well as stiffness work. Fig. 18 illustrates a simple xylonite model constructed for torsional stiffness investigations.

The effort to apply such model techniques to space structures has in recent years been paralleled by the development in America of three-dimensional photo-elasticity work. It has been found that certain materials

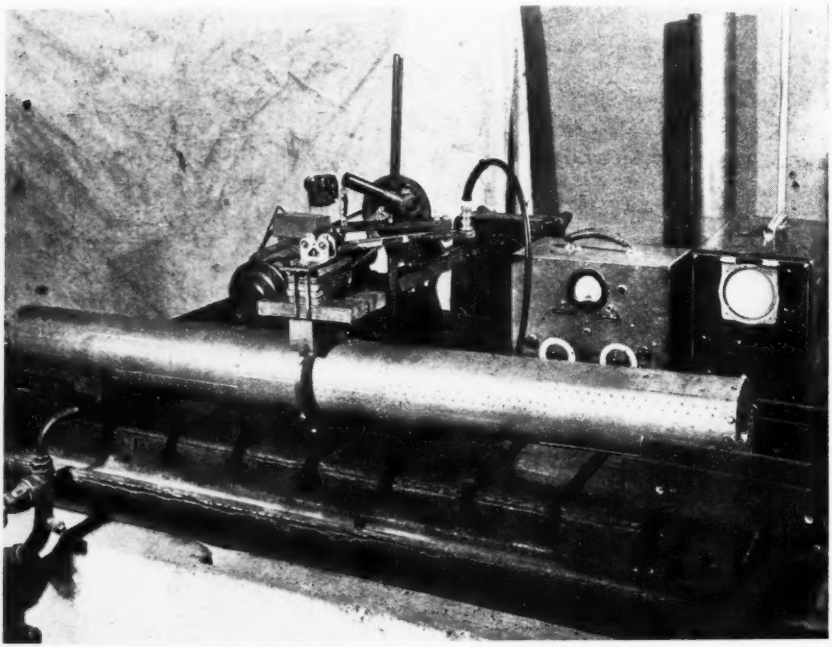


Fig. 17

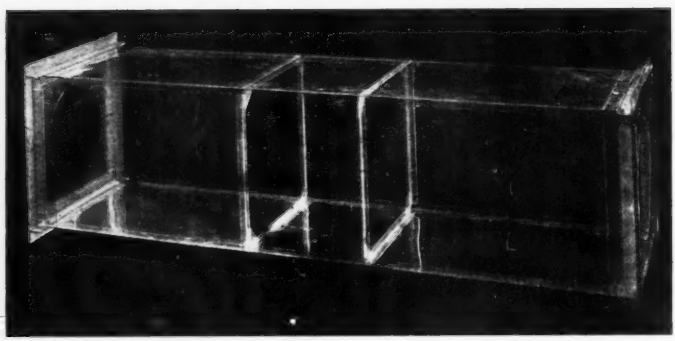


Fig. 18

(notably catalin) are capable of retaining the stress patterns typical of earlier photo-elastic work *after unloading*, provided the loading is done at a moderately high temperature (about 70°C.) and the specimen then cooled to room temperature before unloading. The result is a "frozen" pattern that remains sensibly unaltered for some time after loading. This property is utilised for the treatment of space structures. After "freezing," the specimen is cut into slices suitable for the study of the patterns in them in the ordinary plane stress way. There is no doubt that this is a development of great interest, though some problems of technique

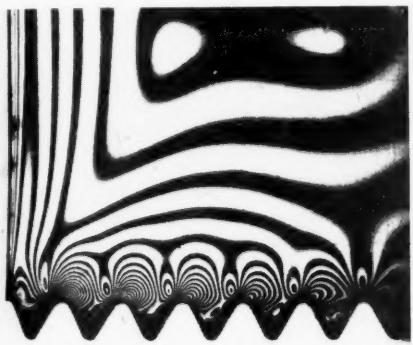


Fig. 19

and interpretation have yet to be overcome for precise work. Messrs. Boulton Paul have been experimenting with the method for some time, and we have also made a start. Fig. 19 illustrates the result of testing a threaded specimen of the bolt and nut type (two dimensional) and then freezing it.

The great ease with which models of xylonite and similar materials can be fabricated has suggested their use for vibration experiments. One of the major difficulties of experiments on flutter has been the construction of suitable wind tunnel models, and xylonite may now be found helpful. A rather simpler proposition is the construction of models for observations on natural frequencies and modes. All that is required here is similarity of inertias and stiffnesses; and earlier models have been built up of metal tubing. A recent very successful model of this sort has been constructed of welded steel bar by the Bristol Aeroplane Company for exploring the frequencies and modes of a large multi-engined aeroplane.

Model work of the character I have discussed here has always seemed to me to have two uses which have been insufficiently exploited in the past—it is often capable of excellent qualitative work, itself of great practical value, and when used in that way provides also an excellent tool for educational purposes.

Flight Work

Experimental effort in flight has been so heavily devoted in the past to aerodynamic work that investigations primarily concerned with aeroplane structures have hitherto received little attention. The war, however, has given us new opportunities and we now have a separate flight section at Farnborough devoted to structural and general engineering problems.

Our earliest efforts, now well known, arose out of the unique opportunity that the large size of the Royal Air Force presented for statistical observations on the accelerations and speeds employed during operations. It happened that the development in the U.S.A. of the V.G. recorder, initially for gust investigations, provided us with a simple and effective tool that was already in production. As a result, in co-operation with the R.A.F. and the U.S. Army Air Corps, we now have some hundreds of V.G. recorders installed in British and American aeroplanes, and an effective routine has developed for the taking and handling of the records. This work has of course given us more real information on the loads occurring on service aeroplanes than we ever had before, and has given it to us in a form that can be directly related to the design flight envelopes now used for the specification of strength requirements. V.G. recorder work is a form of operation

research, and several related jobs, such as the recording of vertical velocities in landing, are now in the early stages of development.

The development of wire resistance strain gauges has given us new opportunities for the exploration of stresses in flight. For the measurement of the steady or slowly varying stresses that arise under ordinary flight conditions it is possible to observe the resistance changes brought about in the gauges by simple microammeters, provided these are suitably mounted and damped to eliminate vibration effects. It is of course desirable that the microammeter should be balanced to minimise spurious readings due to the direct inertia effect of accelerations on the instrument mechanism. We have now had considerable experience with flight work using this simple equipment, and employ observation panels like that shown in Fig. 20, which illustrates a fighter installation. By photographing these panels, records of the simultaneous strains of a number of gauges recorded on the microammeter dials and of the simultaneous readings on the speed, accelerometer and altimeter dials, for example, are obtained.

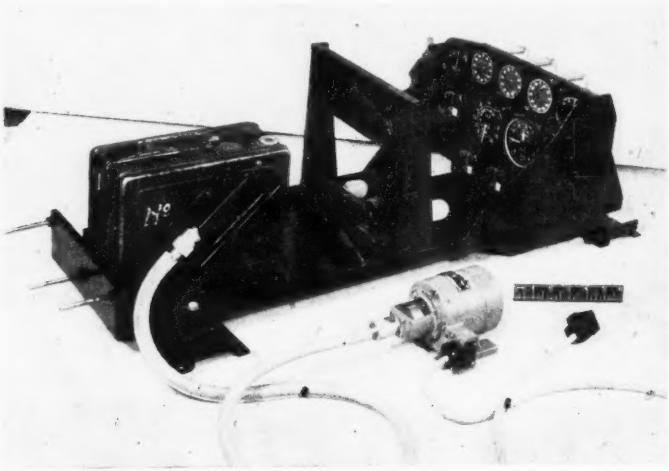


Fig. 20

We have investigated the strains in wing and tailplane spars by equipment of this sort, but it is really best restricted to level flight work and is of course quite unsuitable for observing the rapidly changing strains that may arise from gusts, landing reactions or vibrations. For such purposes, the signals from the gauges are best observed by an oscillograph. A difficulty that arises with this sort of gear is the amount of space it occupies. As a result the number of gauges that can be simultaneously recorded tends to be small, but there are a number of ways of improving matters. By means, for example, of rapid mechanical switching from one gauge to another—rapid, that is, in relation to the rate of change of the signal from the gauge—the results from a number of gauges can be inserted into one cathode tube, the signals representing the fluctuating strains appearing as separate dotted curves for each gauge. Fig. 21 shows a recent installation on these lines, due to H. D. Peirson. We have used gauges and oscillographs in this way for recording strains in wing spars, undercarriages and engine mountings during landing, and for observing the fluctuating strains in wings and tailplanes during ordinary flight, when the fluctuations may

be steady ones due to vibrations or transient ones due to gusts.

An alternative approach to the vibration problem is, of course, to measure vibration amplitudes and frequencies direct, rather than to measure strains. For this purpose the seismograph is the classical instrument, and in its aeronautical form—the R.A.E. vibrograph—has served us well for many years. It suffers, however, from the grave defect that it is unsuited for use in numbers to obtain records of vibration amplitudes at several points simultaneously; and whilst independent records at various positions are useful, simultaneous records of amplitudes, frequencies and phases would be much more

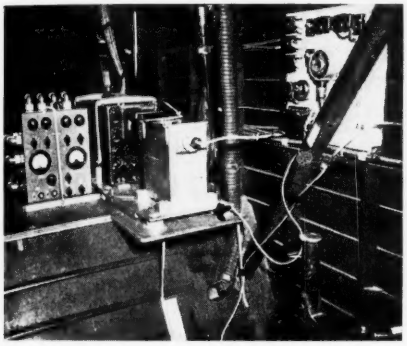


Fig. 21

valuable. For this purpose induction type vibration pick-ups used in conjunction with oscillographs have proved very useful, and we are now planning an installation based on these for observing wing natural modes and frequencies in flight to compare with those measured by resonance tests on the ground.

Pick-ups of both the induction and capacity types have, of course, been used for accelerometers, and these used in conjunction with oscillographs again give a new power to explore simultaneous acceleration readings in different parts of a structure. We are using an installation of this sort to help in the exploration of the behaviour of wings and overhung engines during landing, and later hope to do the same thing for a large flying boat during alighting.

I have touched only briefly on flight work, partly because work of this sort is in an early stage of development. Because it tends to be a costly and lengthy business it is specially essential to put a great deal of preliminary thought into the planning of flight work, to concentrate it upon the most

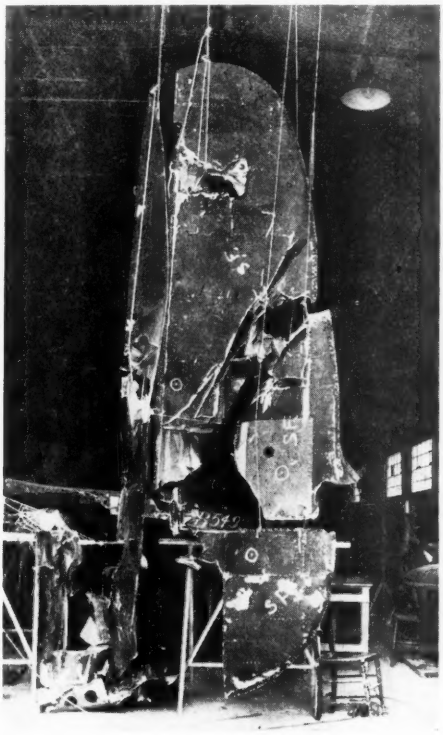


Fig. 22

hopeful lines of development, and to base it upon adequate preliminary work on the ground.

Other Experiments

In spite of all our endeavours, by experiments and otherwise, to ensure the efficiency of aircraft structures, structural failures sometimes occur during flight; and the examina-

tion of the wreckage and its correlation with probable loads in flight and with probable modes of failure constitute an aspect of accident investigation to which aircraft firms and the R.A.E. have always endeavoured to contribute. The simplest forms of accident from this standpoint are those due to obvious faults in design, production or material, which can if necessary be demonstrated by strength tests on similarly faulty specimens; but of course most so-called structural accidents are much more complex affairs. However, it is frequently possible to help in their investigation, even if only in a negative way, by structural tests on the suspected components. Figs. 22 and 23 illustrate such work; Fig. 22 shows the fin and tailplane of a bomber " reconstructed " from the wreckage of an accident, and Fig. 23 shows the same components rigged for a special fin loading test.

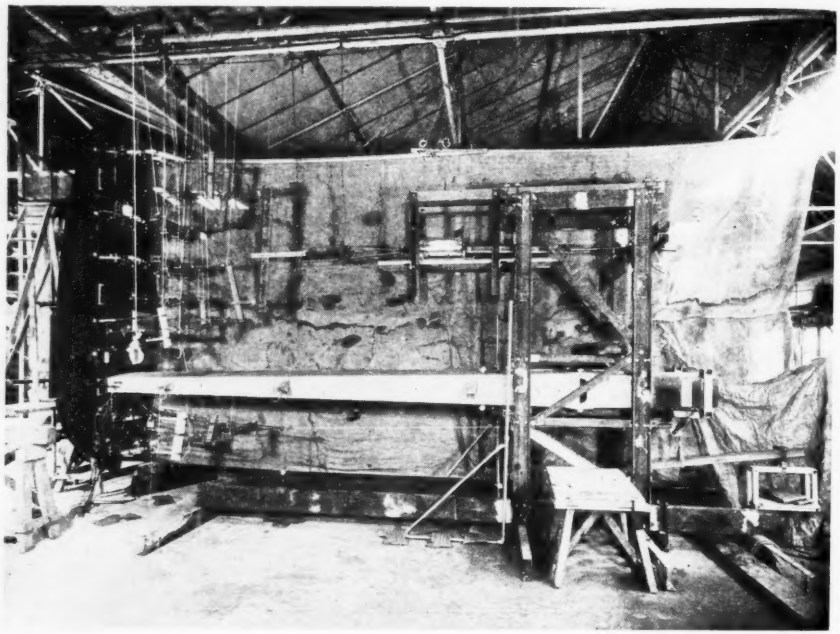


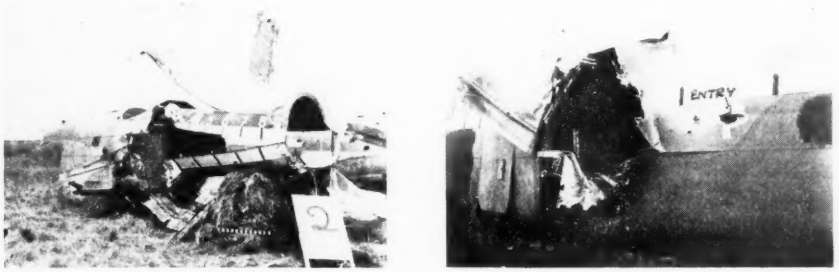
Fig. 23

Such tests refer to accidental damage. We have also during the war conducted many vulnerability tests in which the damage is inflicted by representative shell or shot for the purpose of observing its power to produce lethal effects. These tests involve firing at many wings, fuselages, etc., in a variety of attitudes with a variety of weapons. Opportunities have of course also been taken to study some of the damage inflicted by the enemy on some of our own aeroplanes that have returned from operations, and many interesting and useful results have been obtained. Fig. 24 shows some experiments illustrating the effect of a given size of shell upon stressed skin structures of various sizes, detonation taking place inside the structure. In general, for present sizes of aeroplane and ammunition, aeroplane structures are not very vulnerable.

There are, of course, many other forms of experiment, not usually classed as such, that are nevertheless of importance to struc-

tural design. Some of these are of a statistical nature, involving the investigation of inspection customs and results, as with materials, or the study and experimental manipulation of maintenance operations, all of which may result in increased structural efficiency, whether measured by savings in structure weight or in man-power. It is difficult in a short space to do justice to such work, and I therefore propose to do no more than mention it as of an experimental nature. But in doing so I would like to emphasise how much work of this sort, at present only in an early stage, is needed and how substantial its results could be.

One last comment on an unusual form of experiment. A great deal of experimental work, structural work no less than other forms, is conducted because of a relative powerlessness to carry out the theoretical calculations that the experiment in effect represents—or vice versa. In this sense an *ad hoc* calculation can be regarded as an experiment, particularly if it is done not with



Elenheim Whitley

40mm. H.E. Shell

Fig. 24

Fig. 25

pencil and paper, but by some physical operation. Experiments with the Mallock electrical machine for solving simultaneous equations are of this type, and probably much more of this kind of work could now usefully be done. We are at present experimenting with a battery of Hollerith punched card machines for comparable work of greater complexity. R. A. Fairthorne and I thought about their scientific possibilities in 1938 in relation to problems basically dependent upon linear simultaneous equations, naturally solved numerically by the use of matrices and determinants. Now the pressure of such work arising from vibration, flutter and stressing investigations has given Fairthorne a chance to develop the method in practice. Fig. 25 shows the machine computing room he has developed with the help of the British Machine Tabulating Company.

Conclusion

Though I have covered a fairly wide ground in this lecture, I am very sensible of the fact that I have made no mention of many interesting kinds of experiment made both in the R.A.E. and by the aircraft firms. It is apparent, I think, that structural experimental work is at last "on the map," and I am sure that this owes very much to the encouragement given by the industry as a whole. A number of aircraft firms already have well-equipped laboratories and others are expanding or adding to theirs. So far as the R.A.E. is concerned, the war has given great opportunities, and the future plans for a National Establishment at Bedford will, I hope, provide still more. However much we may value and desire to develop the theory of structures, all will agree, I think, that the present interest in, and expansion of, experimental facilities for structural investigations is bringing new life to the dry bones of the older stressing world.

In conclusion, I would like to express my great indebtedness to the Photographic Division of the R.A.E. for the photographs they have provided. I would like also to say how much the work I have described owes to the encouragement of the Director, Mr. Farren, and his deputy, Mr. Perring, at the R.A.E., and to the never-failing help and advice of Mr. Grinsted at the Ministry of Aircraft Production.

DISCUSSION

Mr. W. S. Farren (Director, Royal Aircraft Establishment: Fellow) accepted the President's invitation to open the discussion because he and his colleagues at the R.A.E. were about to lose Dr. Pugsley, to their great regret, though they wished him every good fortune in the future and appreciated that Bristol University was fortunate in having attracted him. Mr. Farren felt rather in the position of the father of a family who was about to see one of the more successful members of it going out into the wider world.

Recalling the President's suggestion that it might appear that some of Dr. Pugsley's earlier work had been even more valuable than that which he had done during the last four years as Head of the Structural and Mechanical Engineering Department at Farnborough, Mr. Farren said that he personally was so conscious of the great contribution which Dr. Pugsley had made in that Department that he found it difficult to agree with the President: perhaps more reflection might bring him to that view. He felt, however, that Dr. Pugsley would in future do work of his own in his new sphere which would be even greater than that which he had done during the last four years. But he had shown at Farnborough, and Mr. Farren was very grateful to him for it, outstanding qualities of leadership in the very difficult kind of country—one did not like to call it a no-man's land—lying between basic science and hard engineering.

It had become the fashion to say that scientists were valuable men and should not be embarrassed by having to engage in the

more mundane affairs of life, generally described as administrative duties. Whilst he agreed whole-heartedly that men such as Dr. Pugsley should not be expected to deal with the more trivial problems involved in keeping things going, he felt that the task of leading a body of men, of fighting their battles for them when they could not fight for themselves, of looking after their welfare, or seeing that the work they were doing made a coherent whole and that they had an opportunity themselves to take part in deciding what they should do, was administrative work in the true sense. He could testify that Dr. Pugsley had done that admirably.

Coming to the matters covered by the paper, Mr. Farren emphasised the extent to which Dr. Pugsley had found it possible to keep real structural research going in the midst of the vast flow of work which had come to his Department, owing to the urgent needs of the situation in aircraft design and development. The intense pressure which had come from the needs of those who were designing and building aircraft had made it very difficult to maintain real forward thinking. Dr. Pugsley's paper served to show the value of his efforts in that direction. If one pondered over the development of what might appear to be perfectly straightforward pieces of machinery, and considered the way in which intelligent development there had depended on the continuity of research work, one would realise how necessary was a balanced outlook and how important it was to avoid relaxing pressure in research by reason of the needs of the moment.

What was the reward of such work? What did it bring to the profession in whose aid it was done? It might be said that everyone concerned in the design of aircraft should do that kind of work for himself; and Mr. Farren said that he would be the first to support a greater effort on the part of aircraft designers and builders in testing their own structures along the line such as Dr. Pugsley had suggested and described, or by any other means which appeared to them to be suitable. But from his own observations of tests and test results he said he was convinced that an immense amount of general knowledge had been derived and placed at the disposal of designers. He had been impressed by the care and thought which had been taken in the preparation of the tests at the R.A.E., in order that everything possible could be observed and measured, in all probability, as Dr. Pugsley had said, a great deal more than one could ever use. It was safe to say that, due to work of that kind which had been done at Farnborough and elsewhere, the useful load of most of our aircraft had been greatly increased, and that it would have been impossible to effect that increase with safety in any other way. Of course, one could realise the gain in terms of speed, or range, or of greater safety from structural failure.

Acknowledging gladly that the work described in the paper could not have been done without the help of the industry, Mr. Farren said it was their pride at the R.A.E. that when tests were made they were witnessed by their many friends in the industry, who came to watch the experiments on their own material. The only matter about which he was sad was that they could not attend to watch the tests on other people's structures. Perhaps that was heresy; but he would be glad to hear whether others agreed with him.

All at the R.A.E. had been stimulated to greater and greater efforts by the accidents and failures which had occurred during the last five years. During war such failures inevitably occurred at a greater rate than one experienced in peace; there had never been a time since he had been at Farnborough when there had not been at least one major source of accidents to keep them on their toes, and very often there had been several at the same time. The piecing together of the information derived from examinations of accidents, from tests carried out in the laboratories and in the air simultaneously, had been a very thrilling experience, sad as were the circumstances which had given rise to it. We must find ways of continuing such work

without repeating the accidents; in some way or other we must obtain more air experience of what happened in structures, short of actually breaking them.

In conclusion, he offered the meeting's thanks to Dr. Pugsley for his admirable paper.

Mr. J. D. NORTH (Boulton Paul Aircraft: Fellow): By the many devices and methods which he had described, Dr. Pugsley had shown very plainly the difficulty of applying realistic loads in structural testing. The chain of events or the sequence by which the strength of structures was calculated was quite devious; first there was the distribution on a rigid model, and secondly calculations based on necessarily simplified assumptions as to the nature of the structure and the nature of the external loads. One of the big steps which we must try to make in the future was to find some means of applying to an accurately represented structure a better representation of the external forces which came upon it. There were one or two possibly hopeful methods; for example, Dr. Pugsley had shown how, by the use of xylonite models, we had been able to reproduce the details of a structure with great exactitude. The photo-elastic work was only slowly and with difficulty throwing light on some problems. In three-dimensional work if we cut sections we could no longer take isopacs. But those methods regarded as a whole were illuminating the happenings in structures, rounded off by the final experiments in flight. We had waited a long time for a practicable device to measure strains in flight, and one could not help contrasting the simplicity of the strain gauge as used to-day with the complexity of the induction pipe strain gauges which were used on airship work.

Perhaps Dr. Pugsley could say something about the technique of using lacquers, such as stress lac. Mr. North said he had seen some very elegant work performed in America by that process, which was developed at the M.I.T., and which gave a very useful guide as to where to put the strain gauges. One of the misfortunes of war was that it was very difficult to get hold of new materials, particularly from the United States, and he did not think that in this country we had made quite the amount of use of that particular technique which the successes achieved in the United States would justify.

As Dr. Pugsley had said, the experimental techniques ranged all the way from calculations through calculating machines to actual tests, and it was difficult to decide where to draw the line and to say that we were making an *ad hoc* test or operating a calculating machine. It was along the intermediate lines of finding mechanical methods of solving problems which were otherwise impracticable that we might look for considerable further development.

Mr. MARCUS LANGLEY (Fellow): All the efforts described in the paper were directed towards better strength/weight ratios in aircraft structures, or in other words, to the more effective use of material, either because the excess material was carried only at the expense of payload or because some of the materials had been in short supply. The structure was designed in the first place to a certain hypothetical and arbitrary load, and it had to remain in airworthy condition up to the point at which the proof load was applied; it must not collapse before the ultimate load was applied. But what happened then? Under any further increments of load beyond the specified ultimate load, if the specimen were designed only for the one loading, the structure should collapse completely and disintegrate. In so far as that did not occur, the structure had reserve strength. He believed it was possible to analyse that reserve strength and to see how it could arise. It was probably there because a number of different loading cases had to be considered, each of which was critical to a different member of the structure; or it might be there because the designer had deliberately put it there, knowing that the specification would undoubtedly be altered later on; or he might put it there to allow for rigidity or stiffness which was not

covered by the static loading case; or he might put it there because the structure was one which could not be analysed easily. Thus, the designer might provide reserve strength in a structure for many practical reasons not covered by the specified load, as for example handling loads. Reserve strength might be provided because of fear or ignorance. Dr. Pugsley and his staff had done great work in attacking the boundaries of that ignorance; the paper would serve as a guide for many years, and eventually would rank as a classic.

Drawing attention to one or two areas of ignorance which should be explored or in respect of which, if they had been explored, the results should be published, Mr. Langley pointed to the influence of time on the stress which a member would withstand. Undoubtedly, he said, the maximum permissible stress varied according to whether the load was applied only momentarily or over a period of several minutes, as in an ordinary loading machine, or over a much longer period.

Another matter which had to be explored, or if it had been explored the results should be publicised much more, was the effect of corrosion on fatigue strength. The more we designed to no reserve factor, the more science and practice told us how to produce a perfect structure which had no superfluous weight, the more important would influences such as corrosion become and the greater would be the responsibility of the ground engineer who had subsequently to maintain and service the aircraft. The effect of corrosion on fatigue strength was of particular importance perhaps in relation to spot welding, and it would be a daring designer who would use spot welding for a main structure without knowing what could be the influence of corrosion on fatigue strength. We knew little enough about the strength of a spot weld even without corrosion.

Of all the many methods which had been proposed by one enthusiast or another for increasing the range, speed and pay load of aircraft, he concluded, structural research of the kind discussed in the paper would probably pay by far the biggest dividend.

Mr. W. G. A. PERRING (R.A.E.: Fellow): Having listened to the review of the progress of structural research in the experimental field during the last 15 or 20 years, he emphasised Dr. Pugsley's point that modern experimental techniques did not by any means represent finality. We were still only at the beginning of things; there was ahead a tremendous number of roads and avenues down which we should start walking.

In describing the methods of testing, Dr. Pugsley had referred to the early "temple" and to the more recent "cathedral" in use at Farnborough. That cathedral, however, had limitations. It would only tackle aeroplanes of up to about 150 ft. span and 150,000 lb. all-up weight; we were already looking to aeroplanes of twice that size. If we were really to make the best use of the structural materials we had at hand, we must think about ways and means of testing those larger aircraft. That was one immediate problem.

At the other extreme we had also ahead of us the small very high speed aeroplane. We knew very little about the load distribution on that aeroplane, and much less about a great many of its strength characteristics.

There were many detail problems ahead. We could see around the corner the promise of much lower drag, by taking advantage of the possibilities of laminar flow. This aerodynamic problem was becoming also a structural problem. How could a designer produce a structure smooth enough (and capable of retaining that smoothness under load) to give us the advantages that the laminar flow low-drag wing possessed?

In the field of fabrication a large number of problems remained to be solved. The problems of riveting and of various other methods of joining materials together must be better understood.

Sad as it was, the war had afforded an opportunity to study on a very large scale accidents due to "structural failure," and civil aviation opening up ahead of us would

wish to benefit from that work. At the same time, it would introduce its own special problems, including the problem of designing against gust loads on very large aeroplanes.

As we progressed we should become more and more dependent on flight testing as a means of gaining information. We could go a very long way in the laboratory; but with the methods now opening up we should have great opportunities for following up laboratory work by experiments and tests made in flight. The work described in the paper was undoubtedly a most important contribution to future progress and development.

Mr. H. H. GARDNER (Messrs. Vickers Armstrong): During the last five years we had been perhaps getting rather short-sighted. We had been rather inclined to examine one project with a background of production difficulties. Dr. Pugsley, however, had given a proper perspective of structural testing, and it would help us in the future to arrange our structural test programmes much better than otherwise we might do.

In regard to the testing of large wings having spans of more than 120 feet, there had been difficulties concerning wing deflections, and values of the order of 10 ft. had been obtained as tip deflections. He was sure that those could be cut down. At the same time, the reduction of the number of loading points would help materially in reducing the time required both to design and to build a test apparatus. He personally would like to see a definite advance in structural testing gear to enable that gear to be designed in shorter time and to enable the results to be obtained more quickly. Having had a very close association with the stress analysis of aircraft structures during the past few years, he was certainly coming to the opinion that the more we knew of stress analysis the more we required to know from structural testing. He looked forward to structural tests as a means of expanding our knowledge much more quickly than was possible by calculation; and in that connection the test apparatus itself needed a great deal of attention in the future.

A subject on which Dr. Pugsley had not dwelt as much as he would have liked was fatigue, due to repeated loading. In the future, when we should be dealing with civil aeroplanes, we should have to consider the flying life of those aeroplanes as being between 10 and 20 times as long as the present-day life of, say, a heavy bomber. It was highly probable that, due to that increase of flying life. we should be running into fatigue troubles. He hoped to see a great deal of work, both in connection with the design of the gear for fatigue tests and with obtaining more information from tests on joints. We certainly could not have too much experience and evidence from fatigue tests on that type of structural member.

Associated with the problem of fatigue and the repeated loadings that occurred in flight, our knowledge of the actual loads which caused the troubles we had experienced was yet only in its infancy. He looked forward to seeing, as Dr. Pugsley had promised, a much wider expansion of the flight testing of aircraft structures, with that particular point in view.

Mr. R. M. CLARKSON (de Haviland Ltd.: Fellow): He paid tribute from the industry to Dr. Pugsley's Department for the ever-ready help and co-operation they had all enjoyed from it, and which was very much appreciated.

At the moment we had small aeroplanes in the fighter class, flying at speeds of 500 odd miles per hour. A large proportion of the structure weight of those aeroplanes was determined by stiffness. Very soon we should want much larger aeroplanes travelling at such speeds. When we examined the effect of size on the weight of a stiffness-providing structure we found that it followed a law similar to that applying to a structure determined by flexural strength. Therefore, we expected increased percentage structure weights with size. In the past we had been able to cheat that effect on the flexural struc-

ture by spanwise distribution of weight and other devices, but it did not appear at first sight to be so easy to cheat the rising cost in weight of stiffness-providing material with increase in aeroplane size. He asked for Dr. Pugsley's opinion on the possibilities of cheating that law from the design point of view; further, he asked whether, if it could not be cheated effectively, a different attitude would arise towards materials, so that we should be seeking to improve, not the ultimate and proof stress per unit of weight, but rather the modulus per unit of weight. If so, what were the possibilities in that direction?

Mr. DIXIE KEEN (Messrs. Armstrong-Whitworth: Fellow): Speaking as one who had to interpret the results of structural tests to a large extent, he said he felt that the testing of structural components could be divided mainly into two broad parts. The first, which had received great prominence during recent times, was the testing of existing structural components, which had enabled considerable improvements to be effected in respect of the structural weight of existing types.

If the present state of emergency were ended fairly quickly, as we all hoped it would, there was no doubt that the numbers of aeroplanes in production would be considerably reduced and we should be committing ourselves again to drawing board designs. That brought us to the second sub-division, *i.e.*, testing for the purpose of assisting the initial design. We should have to consider ways and means of speeding up results of testing, because unless we could test more quickly we could not wait for the results of the tests on a complete wing and fuselage in the "cathedral" before proceeding with the design.

Whilst Mr. Keen agreed that it was very desirable that more work of a pioneering nature should be done by the aircraft firms, he pointed out that they would need very much bigger staffs of specialists. On the other hand, the R.A.E. at Farnborough was a vast organisation, having several sub-divisions. The Mechanical Engineering Department, for example, had experts on flutter, fatigue of materials, and so on, and they were men who had made the investigation of such problems their life's work. He felt that one could be a little too optimistic about expecting the aircraft firms to bear a very much bigger share of the burden of the pioneering work, much as they would like to do it. Indeed, they would find it very interesting, but when they had to look after the nuts and bolts and the plumbing, and so on, it was difficult to find the men to do the pioneer work and to solve simultaneous equations.

Commenting that many people, particularly on the Government side, were anxious that they should all get together, he said he did not wish to indulge in politics, but he was afraid there was still a very large element of competition and that firms were still a little timid about giving away their closely guarded secrets. He personally believed it was to the good of the country that they should all get together; but it was an open question how far that would be achieved, desirable though it might seem.

He asked Dr. Pugsley to say a few words on the problem that his structural tests were taking us into the range of material strengths commonly known as the plastic range. As soon as the point was reached when the linear law of deflection, *i.e.*, stresses proportional to strains, was no longer true, calculations became much more complex. There were already strain-energy troubles, structural redundances, and so on; but when we had plastic range added to redundances he did not know where we should get. It seemed almost that in the end we should have to throw away our slide rules and pencils and paper, and design on the results of ultimate strength tests, or else introduce a working stress factor as was more usual in Civil Engineering.

Mr. S. SCOTT-HALL (A. & A.E.E.: Fellow) contributed: He was particularly impressed by Dr. Pugsley's remarks on the lessons to be learned from other spheres of engineering.

Recent intimate contact with mechanical and electrical engineering activities had convinced him that if aeronautical engineers confined their own interest solely to the sphere of aeronautics many aircraft developments which would otherwise come very quickly, might be delayed.

The pressure of war had made it very difficult for anyone to follow the developments of other branches of engineering, but no doubt the return to peace would make this very much easier. Any efforts by the Society to maintain the closest possible relationships with the other engineering Institutions would no doubt help very materially in this way.

During the past three years he had had considerable contact with Dr. Pugsley's Department, in connection with strength testing of aircraft armament equipment. Whilst such tests had not perhaps involved the use of any strikingly new techniques, it should, he thought, be recorded that invaluable work had been done in solving such problems as the hang-up of bombs under severe launching conditions, and the strength of aircraft panelling under gun blast. His Department has also undertaken a considerable amount of vibration investigation on aircraft weapons generally. In connection with this last activity he would like to ask Dr. Pugsley if the interpretation of laboratory vibration experiments was now fully understood. He recalled a case where in testing a very light cased container the ground experiments all indicated very early failure due to fatigue. These tests were, of course, made under stress conditions approximating to those to be encountered in flight. The subsequent flight experiments, however, showed that the life of the container was in fact completely satisfactory. Were such discrepancies now avoided?

Dr. H. L. Cox (National Physical Laboratory: Fellow) *Contributed*: Everyone must agree with the author that, however many tests of complete structures might be made, a proper procedure for testing components and synthetising the results was a paramount necessity. In this respect the structural engineer had not been well served by the makers of testing machines. Any testing machine consisted of two parts, the weighing machine and the loading rig. So far as the weighing machine was concerned there was little to criticise, modern machines fulfilling reasonable standards in this respect; but the loading rig, that was, the structure through which the load was applied to the test piece, was much less adequate. Indeed, it was scarcely too sweeping to claim that no testing machine at present on sale was capable of making a compression test "between flat parallel platens," in the usually accepted sense of that phrase. The writer had tried several machines by various makers both British and foreign and he had found them all wanting. If this experience be doubted, let the doubter take a round rod about $\frac{1}{2}$ inch in diameter and about 12 inches long; let him screw one end into the centre of a flat plate about 8 inches square; let him tie this plate by four equal wires one from each corner of the plate to the base of an hydraulic jack, so that the end of the rod be held against the top of the ram of the jack. Then let him operate the jack and marvel at the result. To evade the faults of the testing machine by making test-pieces as boxes was good practice and bad economics: the test piece was at least four times as expensive, and the costly testing machine was used to no better purpose than would be served by a simple jack. The writer's effort to meet these difficulties had been only partially successful, but he hoped to try again in the near future. Meanwhile, Mr. W. S. Hemp at Bristol Aeroplane Co., had looked more closely into the requirements and it appeared that these were not so stringent as the writer first thought. It seemed that the necessary characteristics of the testing machine might be specified and that the manufacturer should be able without undue trouble to fulfil this specification. This matter in respect of the compression testing machine, particularly for tests on flat ended panels and struts, should be decided satisfactorily in the

next year or so; but similar considerations were involved in the design of the other machines of which the author had forseen the need. It was strongly to be urged that the design of these machines be thoroughly thought out at the beginning, so that time need not be wasted later in testing the testing machine in place of the test piece.

Mr. W. E. W. PETTER (English Electric Co. Ltd.: Fellow) *Contributed*: Much of the aircraft test work was necessarily of the large scale *ad hoc* type which, by virtue of its immediate interest and special problems raised, would always occupy a prominent place when testing was reviewed. Nevertheless, from the designer's point of view, a great deal of the most useful work was the result of relatively small systematic tests such as those carried out some years ago on stiffener-panel combinations. Certain Structural Data Sheets which have been issued during the war were excellent examples of the presentation in a form useful to designers of data relating to those structural problems which all had to deal with and which, but for the systematic work already carried out, would necessarily divert effort from new and more pressing problems. The continuation of this systematic work and the good compilation and presentation of it is most important, and indeed it was worth asking the question after the completion of every *ad hoc* test as to whether some information had not been derived which might be of general application, in combination perhaps with the relevant results from other tests.

He would like to join with Dr. Pugsley in stressing the importance of strain gauge measurements. These undoubtedly had an ever-widening field of application and one which had already proved fruitful was in the measurement of stresses in complex castings or forgings in which the assumptions of ordinary stress analysis might be questionable.

Dr. S. C. REDSHAW (Boulton Paul Aircraft: Fellow) *Contributed*: He thought the paper had provided the Aircraft Industry and Research Establishments with a most interesting and informative Summary of aircraft structural research.

The comments made by Dr. Pugsley regarding Model work were particularly interesting to the writer who believed that this was a very neglected feature of structural research. Model work possessed the important advantages of saving in time and cost over full scale testing and also the enormous advantage that a model structure could be built, tested, altered and re-tested before the actual design had left the drawing board.

Dr. Pugsley remarks that the rubber model technique had not been used as generally as one might have expected was a comment which could equally well have been applied to model work in general. It was curious that an engineer was often prepared to accept a mathematical solution, often based on the most approximate assumptions which did not state the magnitude of the error involved, yet declined to use a model technique if the error were known to be of the order of 10—15% of the real values.

There was one great disadvantage in the structural testing of aircraft structures; the applied loads had usually to be estimated from wind tunnel data and then applied to the structure in a manner which was an approximation to the aerodynamic distribution. The writer believed that, with the use of larger wind tunnels, the time was not very distant when strains would be measured on scale models of aeroplanes while undergoing wind tunnel tests.

REPLY TO THE DISCUSSION

Dr. PUGSLEY: Dealing first with the emphasis which had been placed on the importance of expanding and furthering experimental work in flight, he said that after he had drafted his paper he had received a report from America. Normally one supposed that the Americans were doing a great deal of work in flight; the report indicated that they felt they should be doing a lot more. He

looked forward to the time when a great deal more of that work would be done at the R.A.E. than had been done in the past, with as close a collaboration between the theoretical and experimental sides as had developed with laboratory testing.

The remarks of Mr. North and Mr. Perring had brought to his mind the growing importance of the interaction of deflections of structures and the loads on them. Some long time ago Dr. Roxbee Cox and himself had tried to look forward to a position—presumably the technical staffs of aircraft firms would not look forward to it!—in which the loading calculations were wrapped up from the start with the stiffness calculations, just as they were already intermingled in flutter calculations. He hoped we should avoid such complexity, or at least greatly simplfy it; but he did feel that, with increasing speeds and the concomitant increasing need for reduced structure weights, and with the increasing tendency to use materials of high strength but with no change in their fundamental stiffness properties, we should be led to a position in which it would be more and more important to consider deflections as well as loads and in some cases to consider them together.

The R.A.E., in collaboration with the aircraft firms, had done a little stress lacquer work. Mr. Jones had been largely responsible; but it had been found difficult to find staff who were happy to bear with the unpleasant smell of the lacquer and who at the same time were skilled in the art of spraying. The acquisition of the art had proved quite a difficulty initially, and he believed that that was the experience of others. However, he agreed with Mr. North that that sort of work, used as a qualitative guide as to where to study strains in more detail by strain gauges, should be used more than in the past.

Dealing with Mr. Langley's point that, as structures became lighter for a given performance, incidentals or matters which were now regarded as incidentals, such as corrosion, would become more important, he said that inasmuch as the life of the military aeroplane was not long, that was perhaps a reason why the emphasis on corrosion had not become greater. But with the longer lives which were anticipated for civil aeroplanes after the war, coupled in some cases with the continual flying they might have to do at comparatively low reserve factors and with the fatigue problems arising therefrom, corrosion problems would become more important.

With regard to Mr. Gardner's emphasis on the importance of advancing the design of testing gear generally, Dr. Pugsley had hoped he would have mentioned the equipment which Messrs. Vickers had made for themselves some years ago for dealing with the large deflections that arose in wing tests. A written paper on this special testing rig for aeroplane wings would be very valuable.

In that connection Dr. Pugsley mentioned a point which had been hinted at by Mr. Gardner, that the more we knew about testing the more was the behaviour of the test specimen wrapped up with the behaviour of the test rig or the testing machine. As we tried to learn more of compression panels, the more we were learning about testing machines, and he believed we should notice that also with large frames. At Farnborough they had commenced to study the exact mode of breakdown of a wing in the cathedral. The work had not yet proceeded very far, but he believed they would soon find themselves studying the behaviour of the cathedral as well as the behaviour of the test specimens.

He agreed with Mr. Gardner's remarks concerning the importance of the fatigue testing of structures and shared with him the view that not sufficient had been done in that direction. He looked forward to the time when there would be available at the R.A.E. large fatigue testing equipment for dealing with structures as well as for dealing with materials.

Mr. Clarkson had wondered how we could dodge the apparently inevitable law that structure weights for a given size would go up with increase of speed. Dr. Pugsley said he supposed there was one small step that would

help, that with the increasing desire for smooth wings, and for thin wings to minimise compressibility effects, we should naturally find the covers getting thicker; as soon as they passed beyond the thickness we were accustomed to four years ago, when buckling had occurred at an early stage of loading and in fact was present in small degree in level flight, we should automatically get away from the falling off of torsional stiffness due to early buckling.

All would join in the hope expressed by Mr. Clarkson that we should see ways of changing the fundamental stiffness properties of materials. We should encourage in particular any research which promised to lead to higher values of the modulus in shear. If Dr. W. D. Douglas or Dr. Chalmos had joined in the discussion they might have pointed to a glimmer of light on this matter.

We might also derive some help from a further study of a problem which was appreciated long ago, though we had done nothing about it, *i.e.*, that for lateral control we were still using ailerons, devices which produced heavy torques on the wings, necessitating a severe stiffness requirement. A good deal had been done some ten years ago on alternatives to ailerons, or at least on methods of lateral control which did not involve high torsional actions on the wings. If more research were done in that direction now it might give us a lead.

Taking a cue from Mr. Keen's remarks, Dr. Pugsley acknowledged how much he and the staff of his Department at Farnborough appreciated the collaboration of the aircraft firms; he looked forward to even closer contact with the firms as their own experimental work expanded, as he hoped it would. Speaking quite unofficially, he said he hoped there would be more interchange of staffs between the firms and the R.A.E. He appreciated that under war conditions it had been practically impossible; but some of the younger members of the staff at Farnborough would appreciate such exchanges, because it would give them an understanding of practical conditions which it was impossible to acquire in any other way. At the same time, perhaps some members of the firms' staffs would welcome opportunities for research work.

To Mr. Keen's question as to what we should do when we tried to analyse structures in the plastic condition in order to understand better the gap between proof load and ultimate load, he confessed that he had no ready answer. In other connection recently, Professor Southwell had said he felt that 5 or 10 years hence the theory of plasticity would be leading experiment, instead of *vice versa*; and one hoped that that would come true. Dr. Pugsley added that whilst it was not the custom in structures generally to allow for re-distribution of stress due to plastic effects, it had been done in special cases with considerable success in an approximate fashion. Of course, in general structure work one was dealing normally with mild steel, and the situation was no doubt easier on that account.

He very much welcomed Mr. Scott Hall's remarks on the importance of close contact with other branches of engineering. No doubt, as he suggested, the Society might help by fostering contacts with kindred engineering institutions.

Mr. Scott Hall's reference to the vibration testing of armament "stores" raised some points of interest. He did not think we had yet advanced very much since the experience he quoted. It was true that we had made more vibration measurements in flight in the region of such stores to provide a basis for their laboratory testing. But he rather felt we might have to go further, and sometimes obtain in flight, strain gauge records of the fluctuating stresses in the stores themselves, and then adjust our laboratory tests to produce comparable stresses.

He was glad that Mrs. H. L. Cox had emphasised the importance of developing the design of testing gear. This was an area where theory and practice could usefully go

hand in hand more than they had done in recent years.

Mr. Petter had referred to the general information that might often be derived from *ad hoc* tests. He quite agreed with the desirability of noting and disseminating such information. Mr. Petter would be pleased to know that during recent months we had been able in the Department to set aside a small staff to concentrate on this aspect of *ad hoc* tests and the first small fruits of their work would be issued shortly.

After underlining the value of model work in general, Dr. Redshaw had pointed to a possible use in the future: the construction of elastic models for strain measurements whilst in wind tunnels. It was tempting to look a little further and consider the use of "breakable" models in blower tunnels for the investigation of modes of failure. Dr. Redshaw had always been interested in model work and he looked forward to seeing his further results in this field.

WING TESTING

A Method of Testing the Wing Structure of Large Aircraft Adopted by Vickers Armstrong

by

H. H. Gardner, B.Sc.

H. H. Gardner, B.Sc., obtained an Honours degree at Birmingham University. In 1929 he joined Vickers-Armstrong as Technical Assistant and has remained with this firm since that date. In 1941 he was appointed Chief Stressman, and in March, 1945, Assistant Chief Designer.

Introduction.

During the lecture on structural testing given by Dr. Pugsley to the Royal Aeronautical Society, reference was made to the work done at Weybridge on the strength testing of aircraft wings, and during the discussion the lecturer suggested that details of this work should be submitted to the Society for publication. This paper attempts to give a brief outline of some of the more interesting developments which have taken place during the war period, together with a few notes on the arguments which led to the adoption of the final form of test gear.

General Discussion.

The lifting surfaces of the aeroplane have always been the major problem of the aircraft designer. The difficulty of obtaining the necessary structural strength for a minimum weight has marched side by side with the difficulty of obtaining satisfactory aerodynamic shapes for minimum drag; in both cases it has always been essential to prove calculations by test. In the early days strength tests were very crude, experiments commencing often with the trial of strength method followed by sandloading on the inverted aeroplane. These all gave information somewhat imperfectly, but were soon replaced by the more elaborate rib and spar tests of the biplane era. It is probable that more types of aircraft have been built based on calculations supplemented by simple tests on ribs, spars, struts and end fittings than by any other method.

The coming of the full cantilever monoplane completely removed the possibility of continuing with the simple form of component tests, as with the highly tapered plan forms immediately adopted no typical specimens could be chosen, nor could the spar test gear in which end loads were combined with the concentrated lateral loads from ribs be used. This immediately led to the conception of the full scale wing test.

The cantilever monoplane wing demanded much greater care and skill in design than the

Paper received September, 1945.

earlier two spar wire-braced biplane if large increases in wing structure weight were to be avoided, also although the overall loading and resultant bending moment and shear force diagrams were more easily calculated the detail stress analysis necessary was multiplied many times with a serious increase in redundancy problems and a corresponding reduction in accuracy. To ensure that minimum weight was maintained without structural weakness complete wing tests became essential.

The majority of these early wing tests were conducted in the Mechanical Test Department of the Royal Aircraft Establishment under the kindly guidance of the late Mr. Gerard whose "Temple" and the loading methods adopted are much too well known to need description here. The later developments which introduced the "Grove" and the "Cathedral" were all based on similar principles, the fixed head, the link and lever system and the hydraulic loading being present throughout.

Fig. 1.

The concentration of the whole industry's major tests in the Mechanical Test at Farnborough soon began to overload the department and cause delay, which the rapid expansion of the country's re-armament programme did nothing to relieve, therefore larger firms began to develop their own test-

ing equipment. At Weybridge several tests were made on fins and tailplanes using the approved Royal Aircraft Establishment methods. As several of these tests were in effect small scale tests of forms of wing construction to be used later a full scale wing test became almost the logical development of the structural testing programme.

Wing Tests.

By this time the firm had gained the experience of designing, in conjunction with the Mechanical Test Department of the Royal Aircraft Establishment, some of the test gear for two wing tests to be made in the Temple, thus not only was the complication of the link and lever system well known, but also the amount of headroom required for its successful operation was fully appreciated. These considerations together with certain limitations of an existing test bed finally led to the adoption of the present form of loading consisting of a small number of concentrated loads applied through hydraulic jacks.

The principle of a minimum number of concentrated loads was first suggested by Mr. Wallis and discussed with the Royal Aircraft Establishment in connection with the proposed test of a large geodetic wing. It could be proved that the test Bending Moment, Shear Force and Torque loadings could be quite accurately represented by a few concentrated loads. Therefore, provided the local inputs would not cause severe overloading of the local structure, the complete wing test could be made in two stages. The first a test on the local surface to ensure that under air loads the ribs and fabric or skin surfaces met requirements, and the second the testing to destruction of the complete wing to prove the overall cantilever strength.

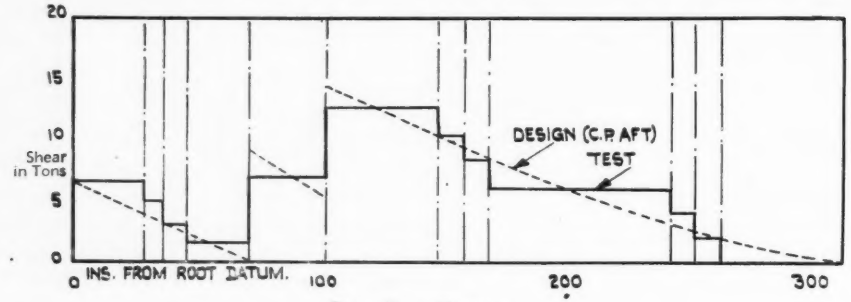
As the first part of the test proved the strength of the local structure special loading ribs could be introduced to distribute the concentrated loads, thus preventing local overloading without affecting the main bending and shear systems. Fig. 1 shows the gear used for the first part of such a test on a medium sized skin covered wing where the strength of the former and skin combination was proved to be satisfactory for the air loads represented by loads in radiating cables and for the skin tension fields by a steel band tensioned by means of a simple toggle lever. The air loads were measured by link gear and a portable weighbridge, whilst the tension fields were measured by the use of several Huggenberger strain gauges.

The second part of the test was made on a test bed with a fixed head. Four hydraulic jacks were used to apply concentrated loads to special loading ribs which distributed each single load equally between three adjacent formers thereby obtaining the close relationship between the design and the test loading conditions shown on Fig. 2. For measuring the value of the concentrateed load applied at each jack—standard Wellington service jacks were used throughout—a ring gauge was developed (see Fig. 3) which recorded loads up to ten tons with an accuracy in this test of considerably less than a half of one per cent.

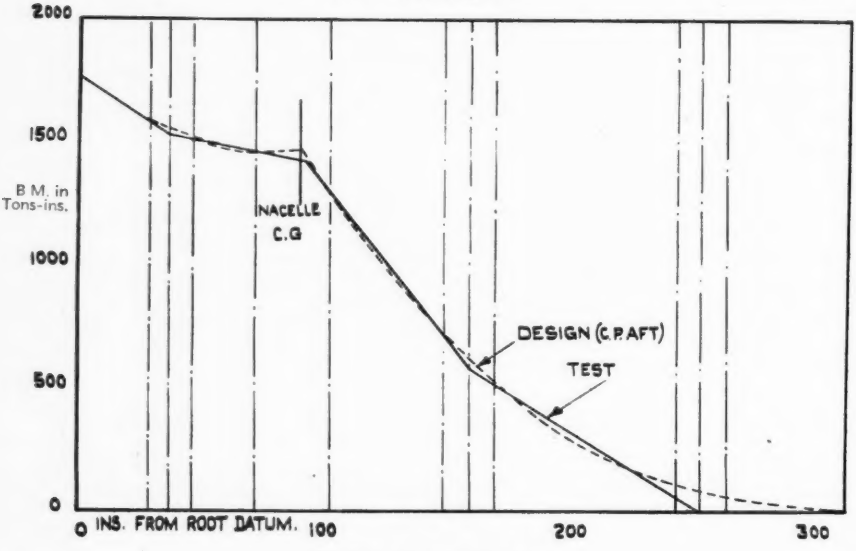
The specimen wing had been designed to fail slightly below requirements; it was therefore anticipated that several loadings would be required after modifications to the structure had been made. The exceptional ease with which the test gear could be dismantled and re-assembled was most valuable in this respect, as the reinforcement of the weakest points usually associated with "Design information tests" of this type was accomplished with a minimum loss of time.

Shortly after the successful completion of the above test a good deal of thought was given to the design of a wing test bed which would accommodate the largest type of wing then envisaged.

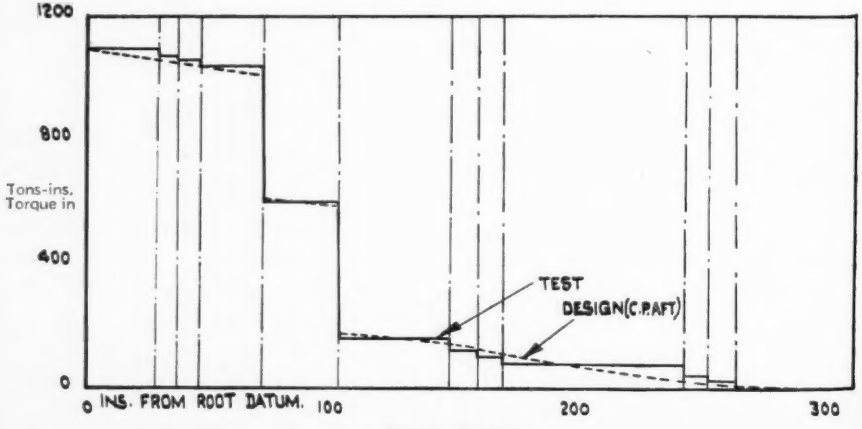
A major difficulty in the previous type of wing test had been the excessive amount of headroom necessary to accommodate the vertical deflection of the wing tip under ultimate loading. As this difficulty would increase with greater spans and higher strength



Shear Force Diagram.



Bending Moment Diagram.



Torque Diagram.

Fig. 2

Design and Test Loadings for Small Wing.

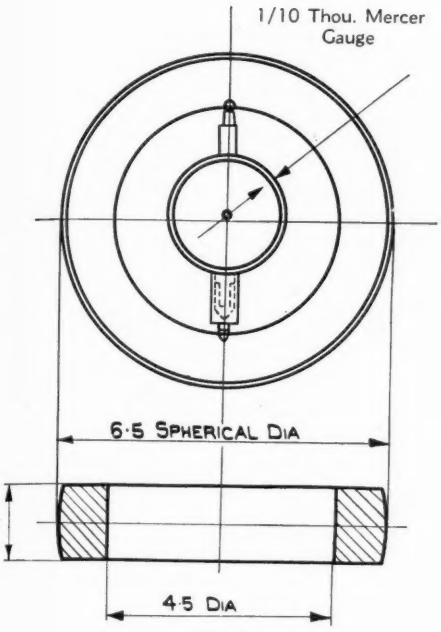


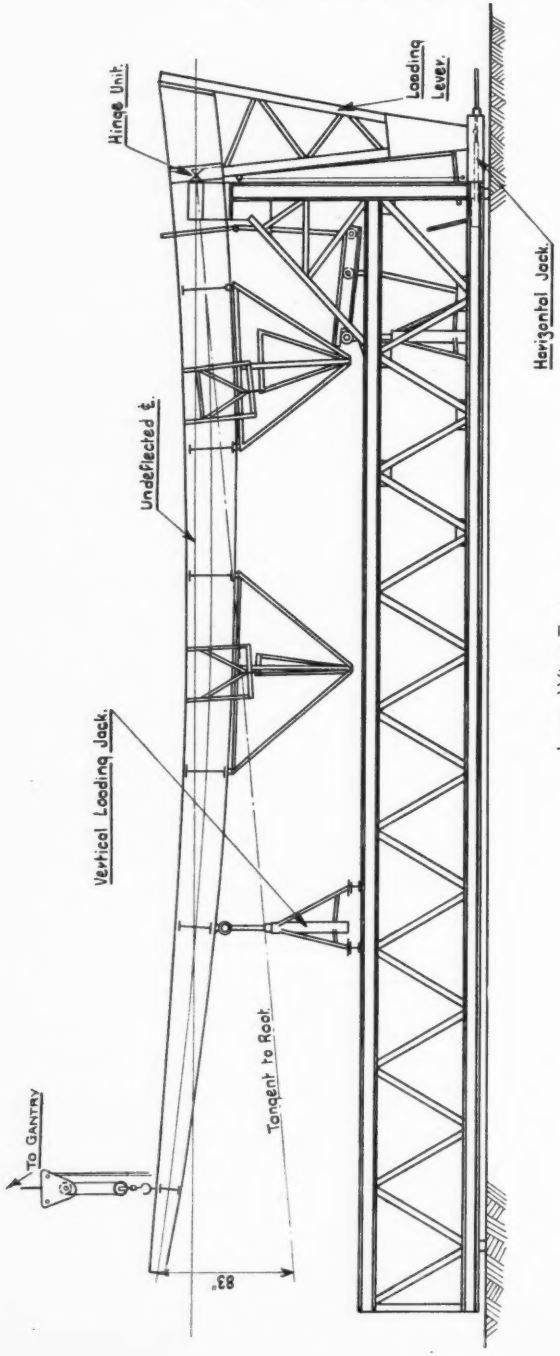
Fig. 3
10 Ton Ring Gauge.

materials a new principle was introduced, the essential feature of which was the movable head of the test bed. By means of a special hinge unit and the adoption of root loading levers a small angular movement of the head could be produced which reduced the maximum vertical deflections to a small fraction of the corresponding fixed head values. Preliminary schemes were drawn and the major points of design fixed, but as so often happens in the aircraft industry priorities changed. A wing test became urgent before the rather elaborate test bed had been completed in the drawing office; therefore it became necessary to place speed before all other considerations and complete a wing test before the prototype first flight. The basic principles of the more elaborate bed were retained, such as the movable head, the hinge unit and the horizontal loading, but features such as the reinforced concrete beams, the pit for the end lever, and several refinements towards ease of operation were abandoned, the test bed being tailored to fit the wing. Further experience has shown that the "ad hoc" type of test bed essential for this test is so satisfactory that it is likely to be adopted for some considerable time.

Details of Final Wing Test.

With the adoption of the above method not only were vertical deflections reduced, but lateral displacements became almost negligible and the work done by the vertical jacks was appreciably reduced. The wing to be tested had a span of 117 feet and ignoring emplacement deflections and strains beyond the elastic limit, with a fixed head the tip deflection would have been greater than 7 feet at ultimate load, whereas in the actual test the maximum vertical displacement of any part of the wing was less than 18 inches. The general arrangement of the test bed is shown by two warren girders braced together by top and bottom plan bracing. The head of the test bed was a heavy steel plate box which carried the hinge and was supported inside the wing by members threaded through the geodetic inter-spaces. The hinge unit shown in Fig. 5 consisted of spring steel plates interleaved at 90° connecting two heavy steel angles, one of which was attached to the head of the test bed and the other to the dummy wing section to which the main wing was attached; this provided a frictionless hinge which was capable of carrying vertical and horizontal shears and allowed a maximum angular movement of 8°. As the maximum required movement of the wing was 6° this was considered to be a reasonable margin.

As shown in the diagram the dummy wing section carrying the vertical levers was rotated by means of a 40 ton horizontal hydraulic jack which was used to apply the main load, the wing jacks being operated to obtain final balance. These were mounted above the main girders of the test bed and were operated by remote controls as no one was allowed under the wing during loading except at the



Large Wing Test
Fig. 4
G.A. of Wing and Test Bed just prior to Ultimate Failure.

root end where adequate protection was provided. The tip load was applied by means of a block and tackle as this gave increased stability to the specimen and permitted a certain amount of movement out of the vertical plane. The ring gauges with which the loads were measured were those already developed in the previous test, but in this case a new mounting was provided which prevented slip due to relative movement of the test specimen and the test bed. Six concentrated loads were sufficient to give the required agreement between design and test loading; these loads together with the two down loads representing engine inertia forces were applied through four standard jacks, as by combining two uploads with one download through a light steel frame or spider one jack could be used to apply three loads. Fig. 6 shows the resultant Bending Moment, Shear Force and Torque diagrams, also the relation between design and test conditions.

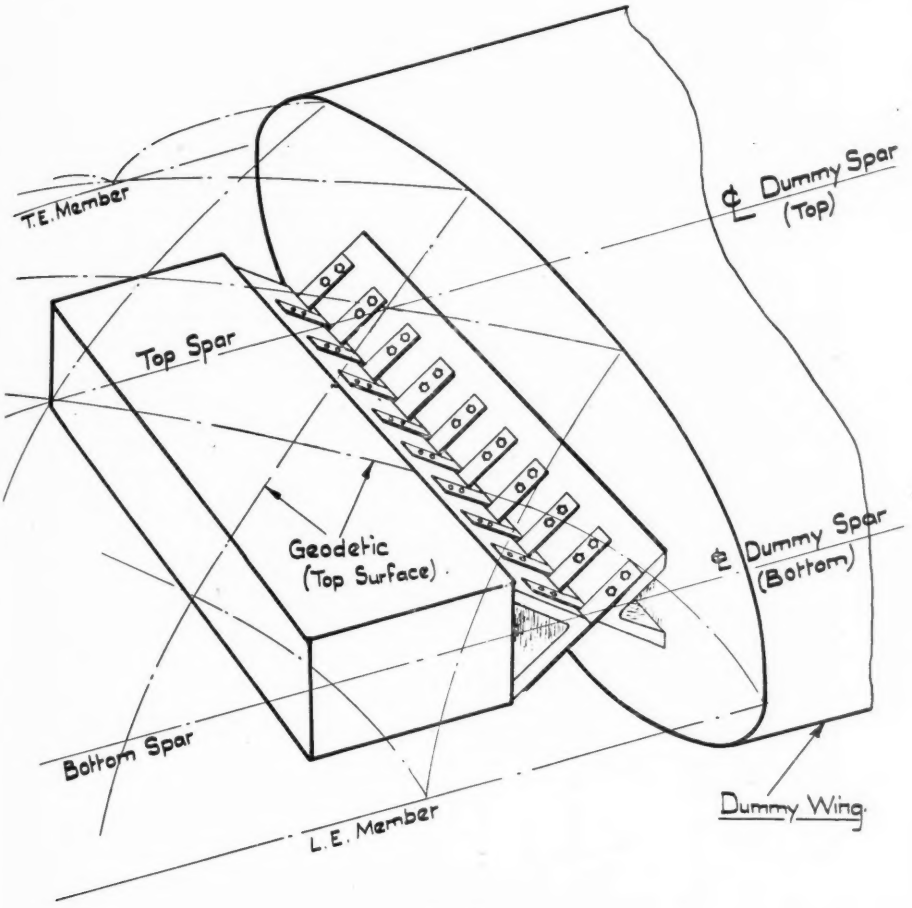
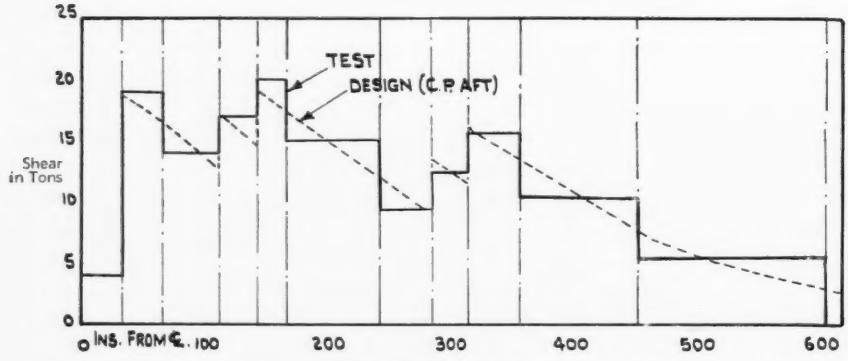
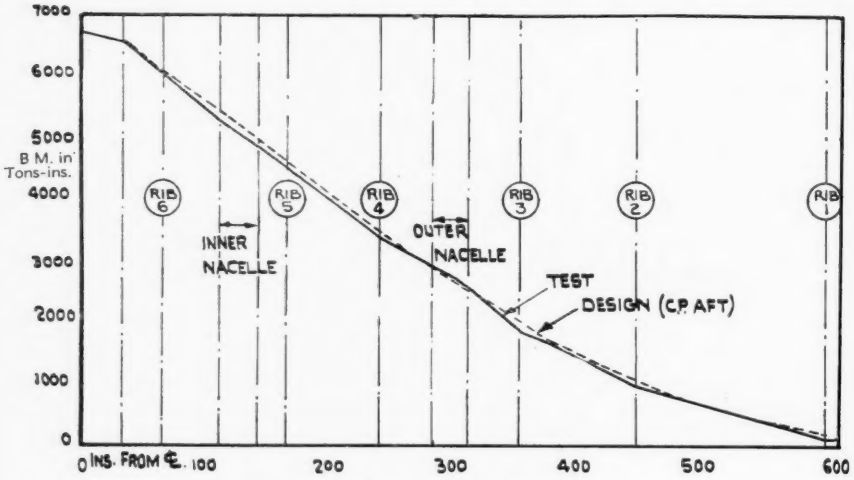


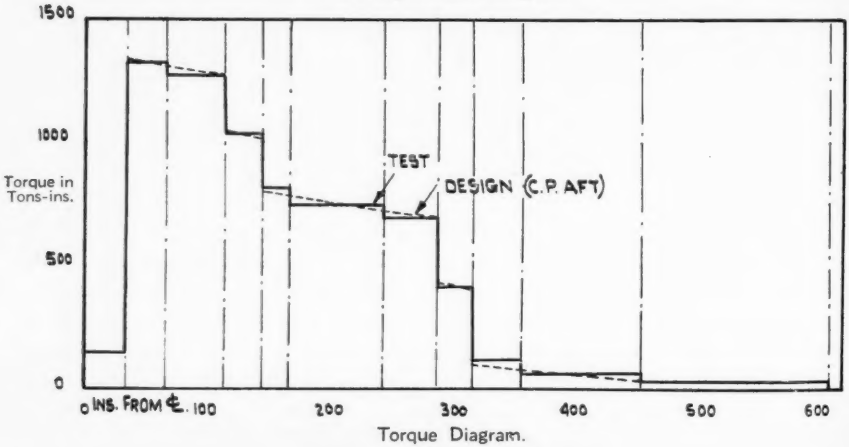
Fig. 5
Hinge Unit.



Shear Force Diagram.



Bending Moment Diagram.



Torque Diagram.

Fig. 6

Design and Test Loadings for Large Wing.

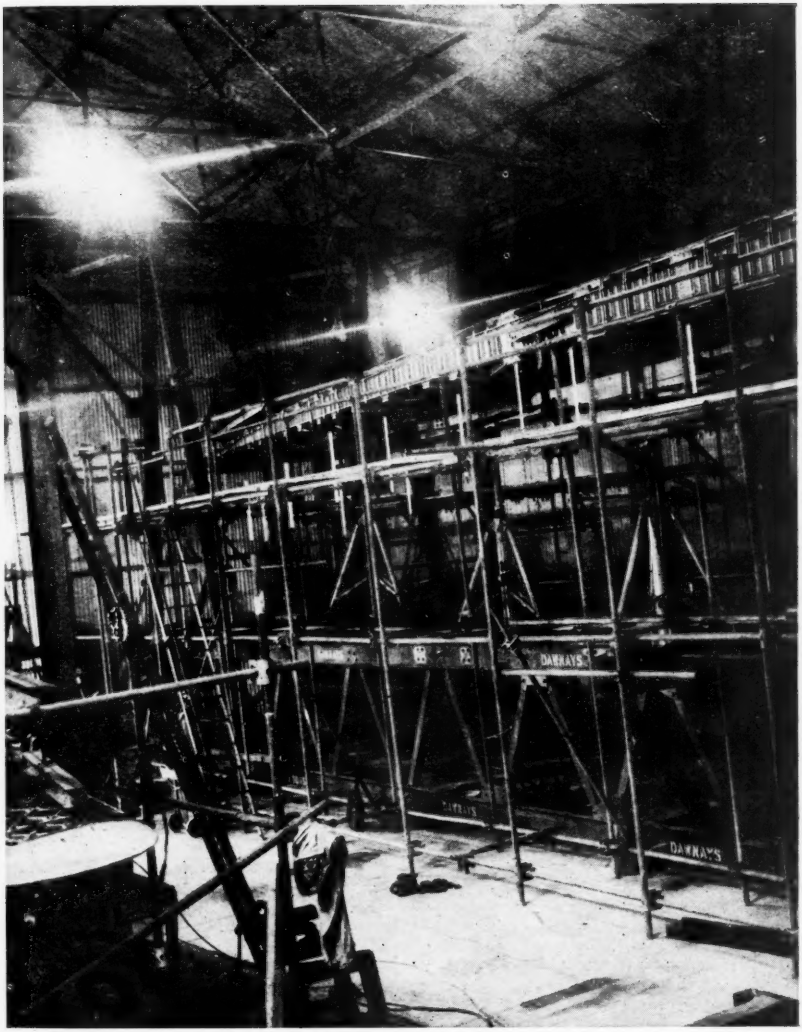


Fig. 7a. Tip End of Rig.

View showing test bed with test specimen in unloaded condition. The vertical end lever through which the wing is loaded by means of horizontal jacks is clearly shown.

After each increment of load wing deflections were observed by means of two Theodolites and a number of scales suspended from the wing structure. The use of spot lights to illuminate the scales enabled a complete set of readings to be taken by two observers in a very short time. The inclination of the root was recorded by means of a clinometer simply constructed by fixing a vertical lever carrying a graduated scale at the lower end to the dummy wing and noting the linear movement of the scale by means of a plumb line, the bob weight of which was immersed in an oil dashpot. Stresses in spar and geodetics were measured by use of both the standard Huggenberger and electric strain gauges; in addition Mercer dials recorded the relative movements of the top and bottom

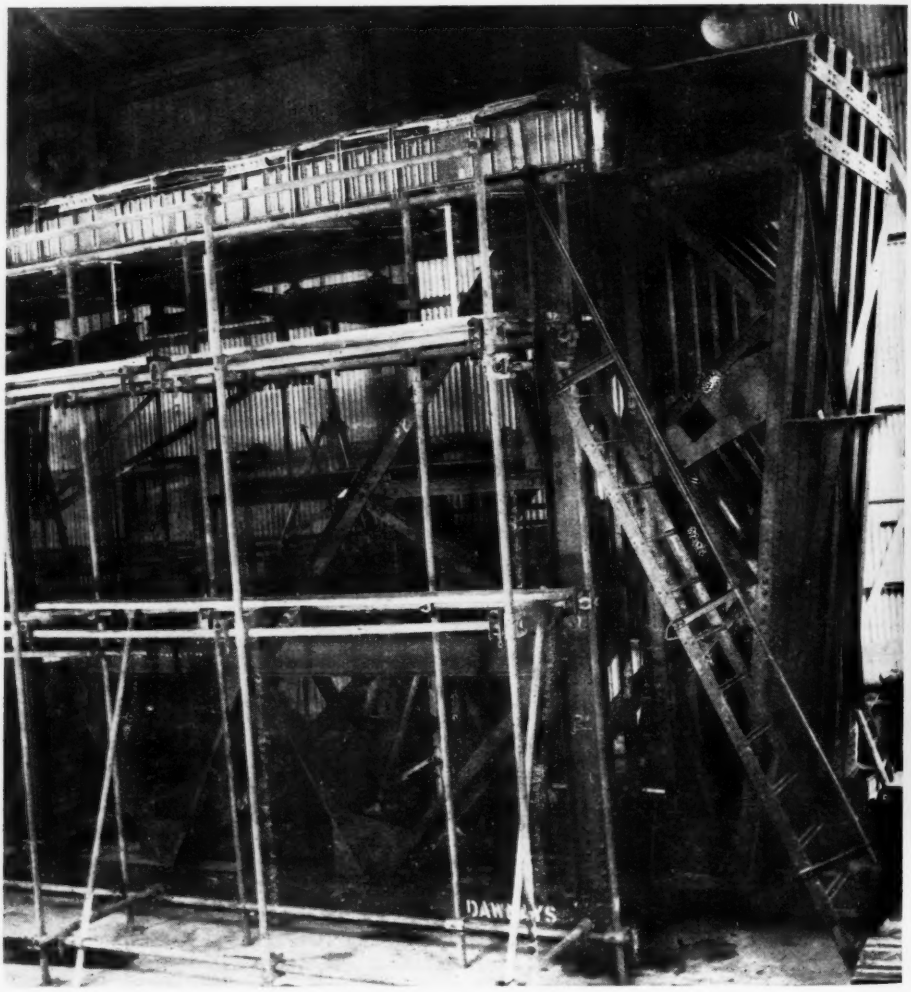


Fig. 7b. Root End of Rig.

geodetic surfaces at the spar section. Whilst a complete set of readings were being taken, independent observers traversed the more highly loaded sections of the spar and geodetics with curvature gauges and recorded the slight change of curvature in all these members. By this means one could "feel the pulse" of the specimen after each load increment, making it possible to predict any instability failure, stop the test and slightly modify the specimen if desired. The control of the test was simplified by the use of a loud speaker which ensured that all operators worked in unison, and allowed one man to keep complete control whilst keeping all assistants informed of the progress of the test. The method worked well, enabling a technique to be established whereby a test could be completed within two to three hours.

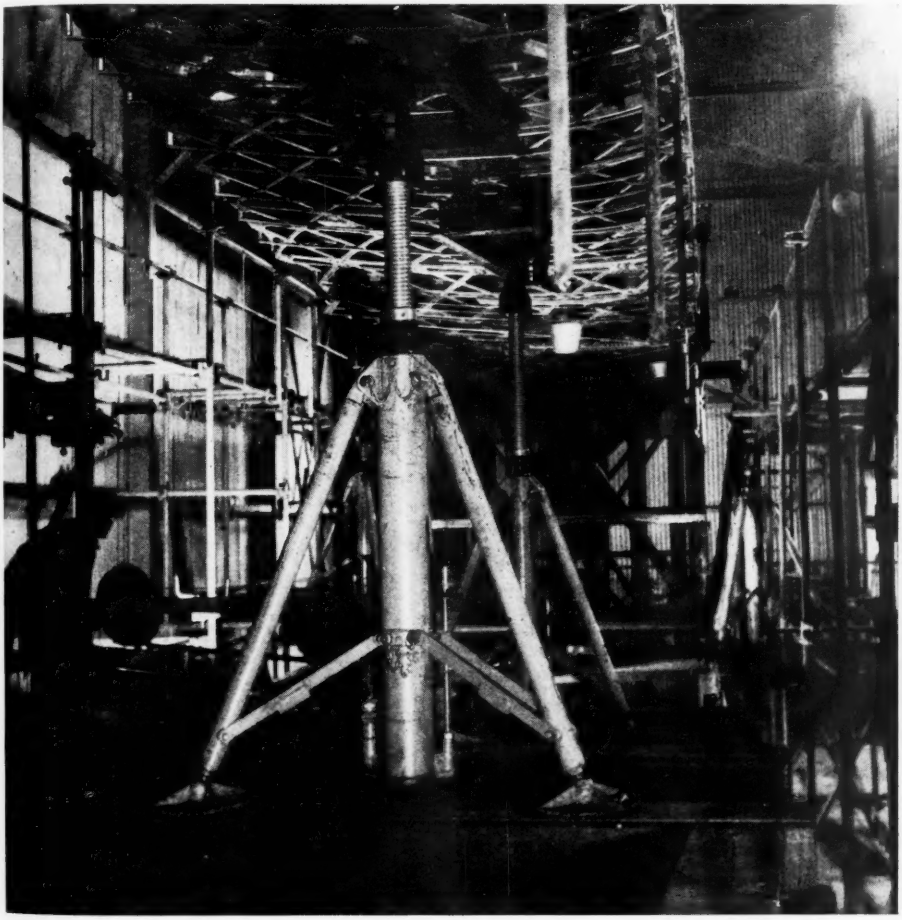


Fig. 8.

An important feature of this "ad hoc" type of wing test was the speed of construction; within five months of the date of com-

mencement of work on the drawings of the test bed the first tests on the above specimen were being made. During this time preliminary drawings had been made by the firm, and submitted to the steel constructors, who from the date of receipt of drawings, produced the whole test bed in less than three months at a cost which was but a fraction of the cost of the test wing.

The bed has now been rebuilt for a new design of wing, by slight modifications to the head and a completely new dummy wing, together with the necessary vertical levers. The photograph shown in Fig. 7 gives an impression of the latest bed whilst Fig. 8 illustrates the simplicity of the concentrated loading gear. This process can be extended as the experience gained in the series of test completed up to the present time shows that the above simplification of loading combined with small wing deflections will enable test gear to be designed and built quickly at a comparatively low cost.

Looking into the future, when possibly the ultimate strength of aircraft structures under static loads may be demonstrated satisfactorily by stress analysis, the need to prove the fatigue strength and the strength under repeated heavy loads of complicated structures will become more and more urgent; it is then that test apparatus similar to that briefly outlined above, with its simplicity of construction and ease of operation, will become of outstanding value to the aircraft industry.

Acknowledgment

The author wishes to express his appreciation of the encouragement given by Mr. B. N. Wallis, who laid down the basic principles described above and under whose direction the preliminary design of the test beds was completed.

AN APPRECIATION

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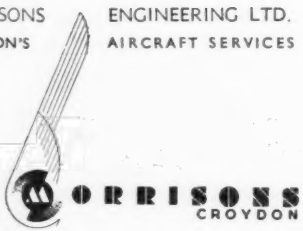

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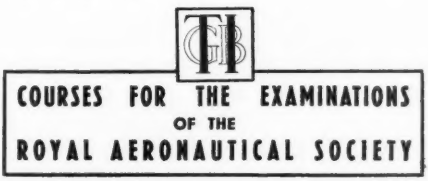

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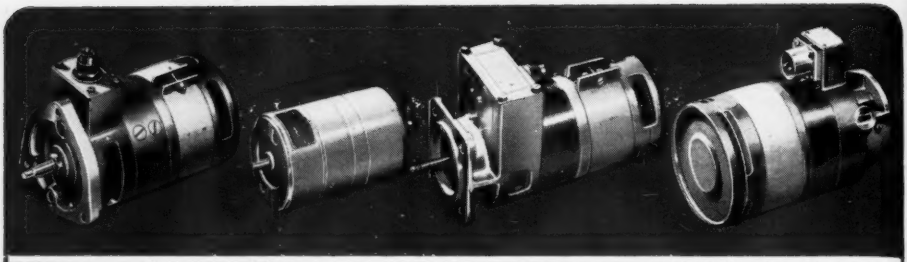

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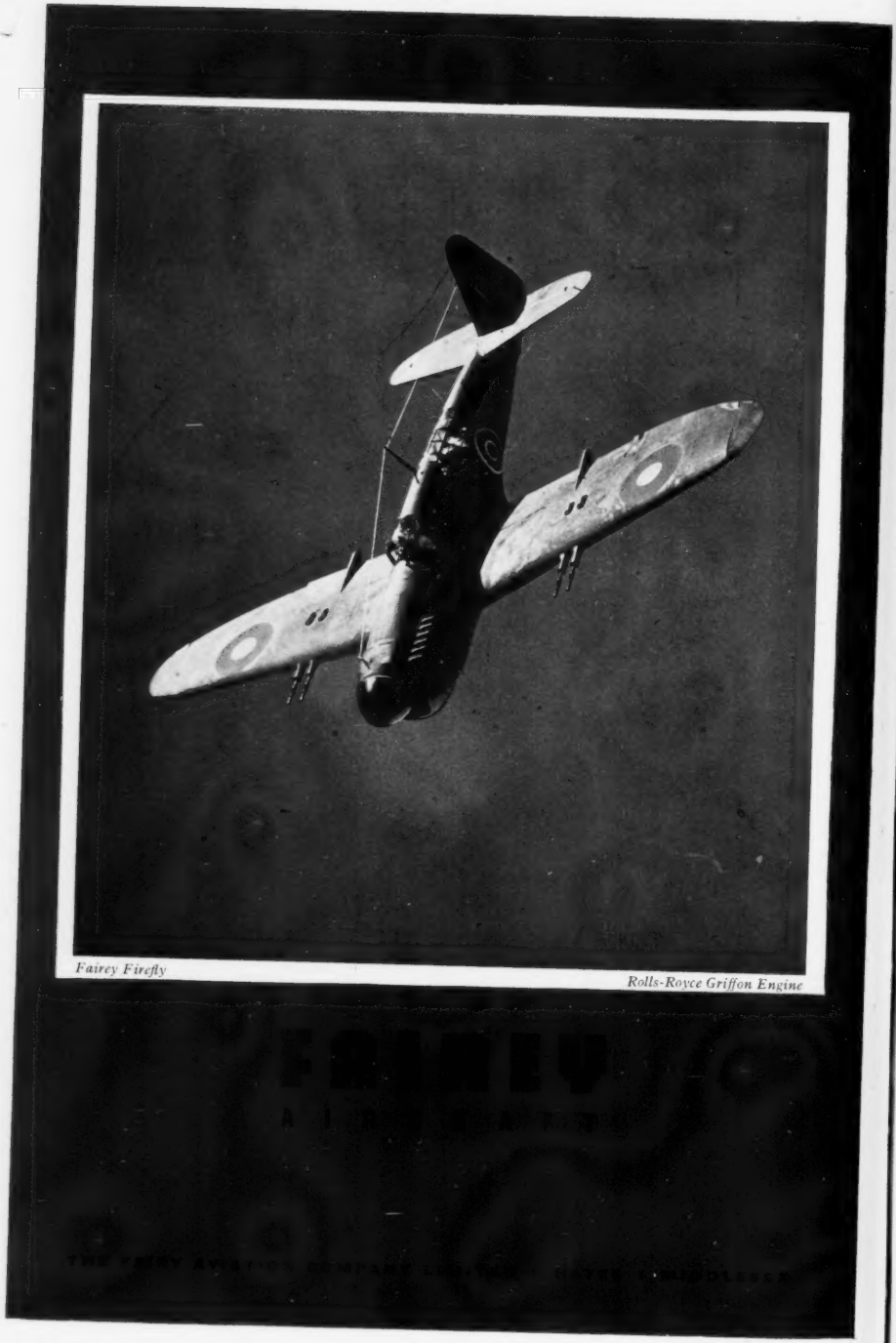

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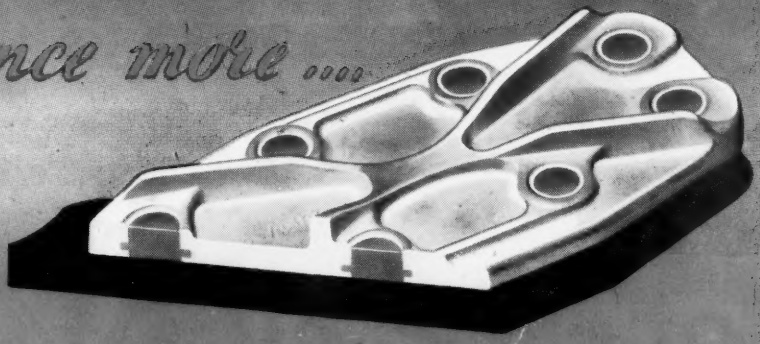

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